REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

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1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	~~26 Oct 98~~	MAJOR REPORT

4. TITLE AND SUBTITLE
SATELLITE ATTITUDE DYNAMICS SIMULATION AND CONTROL

5. FUNDING NUMBERS

6. AUTHOR(S)
2D LT ST PIERRE DANIEL C

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
UNIVERSITY OF COLORADO AT COLORADO SPRINGS

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
THE DEPARTMENT OF THE AIR FORCE
AFIT/CIA, BLDG 125
2950 P STREET
WPAFB OH 45433

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
98-026

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION AVAILABILITY STATEMENT
Unlimited distribution
In Accordance With AFI 35-205/AFIT Sup 1

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

DISTRIBUTION STATEMENT A
Approved for public release;
Distribution Unlimited

19981120 019

14. SUBJECT TERMS

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT

Satellite Attitude Dynamics Simulation and Control (SADSaC)

Written By
Daniel C. St. Pierre
4 May 1998

University of Colorado – Colorado Springs
Master of Engineering

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0.0 Abstract

The Satellite Attitude Dynamics Simulation and Control System (SADSaC) project has two main objectives. The first is to provide a visual demonstration of satellite attitude dynamics. The second purpose is to be used as a learning tool by providing actuator hardware for student analysis and design.

SADSaC is a 22" cube attached to a bearing on a 3' pole that allows for near frictionless rotation about the vertical axis. Attitude control will be done using a dual actuator system of a reaction wheel and gas jet thrusters. Tachometers and an absolute optical encoder will provide sensing capabilities of satellite position and satellite and reaction wheel velocities.

This paper describes in detail the procedures used during design from conception to operation, as well as the modeling and system tests that were necessary to ensure proper operation. Documentation of engineering drawings, mathematical models and component parts ensure easy duplication of SADSaC should the need for more than one arise.

Observing the completed SADSaC system, one can see the control systems battling different disturbance torques affecting the attitude of the spacecraft. Control can be done through either gas jets or reaction wheel. Momentum dumping capabilities are also through the gas jets. SADSaC is an excellent learning tool demonstrating real world control and dynamics of spacecraft.

1.0 Project Definition

1.1 Introduction

The Satellite Attitude Dynamics Simulation and Control System (SADSaC) is a satellite attitude control system and dynamics simulator. Attitude control is necessary on a satellite for pointing accuracy of antennas, lenses or other instrumentation on board the spacecraft. It can be maintained through many different devices called actuators. The actuator that is used depends on the pointing accuracy needed. This accuracy can range from a few tenths of an arc second as in the Hubble Space Telescope, to several degrees for a simple communication satellite. Examples of actuators are reaction wheels, gravity booms, magnetic torquers, and thrusters. The actuator causes a torque on the spacecraft causing it to move in the desired direction. SADSaC uses two actuator systems: reaction wheel and gas jet thrusters.

Sensors are the instruments by which the spacecraft determines its attitude. In a sense they tell the actuators what to do. Like the actuators there are different types of sensors for different pointing accuracy. Examples of sensors are magnetometers, sun sensors and star Trackers to name a few. Magnetometers sense the earth's magnetic field along a certain axis by the current induced. Star trackers and sun sensors look for a light object in space. Star trackers sense the star field and compare with a star map. Both of these sensors generate data for sensing attitude. One of the sensors used on SADSaC, the absolute optical encoder, is not normally found on spacecraft. The absolute optical encoder compares the satellite's position to a fixed reference within the satellite.

Tachometers onboard SADSaC measure the speed at which both the satellite and the reaction wheel spin.

1.2 Project Objectives

1.2.1 Primary Objective:

The project's intentions are to provide a visual demonstration of the method by which satellites orient themselves given a command from a ground station, correct for disturbance torque, and dump momentum from the reaction wheel. This will be a satellite dynamics and control demonstrator as well as a method for studying attitude control for the USAFA's Falcon Sat program

1.2.2 Secondary Objective:

As an engineering project, this project's objective is to provide a learning tool for the designer in areas of control theory, the engineering development process and hands-on experience in design.

1.3 Project Description

SADSaC is a 22" cube with plexi-glass sides and framed in aluminum. The reaction wheel is mounted just inside the cube (satellite) on the top. On the side corners, are mounted the gas jets for maximum torque about the axis of rotation. The inside of the satellite contains all of the necessary equipment to operate the wheel and jets. The satellite itself is allowed to spin about its z-axis, on a bearing mounted to a 30" high stand. The stand is made of 3" aluminum pipe through which the necessary wiring and airline are allowed to pass. Also attached to this pipe and the rotating satellite, is the optical encoder used to measure the angular position of the satellite from a fixed reference. On the stand is an interface panel through which all of the commands are sent

to the satellite. Above the interface panel is a digital voltmeter used to display the angular position.

1.4 System Requirements

In order to meet the objectives of section 1.2, the following requirements have been set. First SADSaC must have similar properties to that of Falcon Sat, specifically the same external dimensions and the same weight, thus producing a similar moment of inertia. SADSaC's movement will be limited to one axis by which it will rotate a full 300° on a near frictionless bearing.

Movement will be done through dual actuator system of gas jet thrusters system and reaction wheel system. The gas jets provide momentum dumping capability for the reaction wheel as well as a pointing mechanism, and the reaction wheel turns the satellite according to the principles of conservation of momentum.

SADSaC will be positioned to within a $\pm 0.5°$ angular position. This will be done by the design of both analog and digital control systems. To do this, the position of the satellite as well as the velocities of both the reaction wheel and the satellite must be available in both digital and analog signals. Position will also be available on a digital display.

The system will be easily portable. This mean SADSaC will be mounted on casters that ensure smooth movement. All external hardware will be attachable to the base while in transportation or be on some other mobile unit such as the computer stand.

The above requirements all are intended to provide the user with a fast simple set-up that is user friendly, while minimizing cost by using available parts when possible.

1.5 Subsystems and Subsystem Requirements

1.5.1 Mobile Stand

The mobile stand is the part that holds the satellite part of the system off of the ground. It is composed of a 3" pipe mounted on four legs with casters. At the top is a bearing that allows the satellite to spin. The mobile stand is required to perform the following functions. First and foremost, it must provide a stable support to the satellite and easy mobility. The stand must also have a mounting surface for the digital display and interface panel. The bearing mounted on the top must be a near frictionless rotational interface for the satellite. Mounting of the satellite on the stand must be easy to assemble and disassemble if necessary. The stand must also have a mechanical stop to limit the movement of the satellite to 300°.

1.5.2 Satellite Structure

The satellite structure is the portion to the system that is intended to use the same dimensions as Falcon Sat. It is a 22" cube (Falcon Sat is an 18" cube) built from aluminum with plexi-glass sides and top. This allows for protection and visibility of internal components. It must provide a rigid mounting structure for the reaction wheel system, gas jet system, power supply, absolute optical encoder and the encoder's digital to analog converter, as well as any necessary ballast to simulate the inertia of Falcon Sat. There must also be an easy interface with the mobile stand.

1.5.3 Reaction Wheel System

The reaction wheel system is composed of the following components; reaction wheel, 12V drive motor, tachometer and servo motor amplifier. The reaction wheel system is required to provide an actuator for attitude control of the satellite and use

the existing components from previous projects. It must also provide reaction wheel velocity to the controller.

1.5.4 Gas Jet System

There are eight gas jets mounted in pairs on the side corners of the satellite. One jet per pair is for clockwise movement and the other is for counterclockwise movement. This is required to provide an attitude control actuator and momentum dumping capability for the reaction wheel. It must run off an external air source. The gas jet system is composed of the following components; eight solenoid valves, air line and air accumulator/dispenser and jet control circuit.

1.5.5 Air Supply System

The air supply system is used for thrust when the gas jets are fired. It must provide a constant source supply to the jets from an external air supply. It must be available for SADSaC to run correctly.

1.5.6 Power

The power system provides electrical power to the electrical components of SADSaC. The power supply runs off AC power from a standard outlet and provides the following DC power for the subsystems; 28V @ 9.0A, 12V @ 10.0A and -12V @ 10.0A. The servo motor amplifier also provides a regulated supply of ±5V. A common ground is provided to all systems via a ground bus.

1.5.7 Position and Velocity System

The position and velocity sensors will provide satellite angular position and satellite velocity to the controller. Position is determined through an absolute optical encoder, while velocity is provided from a tachometer measuring the rate of the satellite

with respect to the stationary center pipe. There is also a difference circuit to make the output from the encoder fit the user's requirements allowing for a position output of $\pm 180°$ vs. a range of 0° to 360°.

1.5.8 User Interface

The user interface is mounted on the mobile stand. It provides easy interface for the following output signals: satellite position, satellite velocity and reaction wheel velocity, and the following input signal: reaction wheel command and gas jet command. There is also an interface for the manual controller and several ports for ground.

1.5.9 Manual Control

The manual control is a hand held remote control that allows a user to attempt to control the satellite by hand. Commands for CW and CCW gas jet thrusters and reaction wheel control are located on the manual controller.

2.0 Specifications

2.1 Specifications for Non-COTS electronics

2.1.1 Introduction

For the SADSaC project, many of the parts are commercial off the shelf products (COTS). Buying parts rather than building them saves money and time, in addition to the fact that they have been tested and proven to work according to the manufacturer's specifications. It was necessary, however to build two electrical circuits from scratch. These circuits are the gas jet thruster controller and a circuit to subtract 1.800V from the analog position reading of the satellite.

2.1.2 Constraints

2.1.2.1 Gas Jet Thruster Controller

Using readily available electrical components a circuit must be designed to take a command signal from either the user or the controller algorithm, recognize if it is positive or negative (for clockwise or counter-clockwise motion) and determine if the amplitude is enough to trigger the gas jets. A deadband must exist so that a small signal will not cause the gas jets to turn on. This deadband must be adjustable for different applications. If the signal is great enough the circuits will send a 12V, signal to the solenoid valves causing them to open and allowing the air to pass through. The counter-clockwise jets will be fired for negative signal and the clockwise jets will fire for a positive signal.

2.1.2.2 Difference Circuit

A circuit must be designed to take the output of the optical encoder (0.0V-3.6V) and subtract 1.800V. Again the components must be readily available. The optical encoder yields angular position in voltage, where 1.000V = 100.0°. For purposes in this design, it is desired that the angular position reading is between -180.0° and +180.0°, therefore a circuit must be designed which will subtract 1.800V for any input from the optical encoder. The output from this circuit is the optical encoder output minus 1.800V.

2.1.3 Specification List

2.1.3.1 Gas Jet Thruster Controller

Size	5"x5"x2" (max)
Potentiometer	50KΩ - 10 turn
Relay	Potter & Brumfield RKA-11DZ-12
Power	+12V @ 10.0A, ±200mV & ±100mA +12V @ 10.0A, ±200mV & ±100mA
Input	±12V
Output	+12V >8.5W, -4V

2.1.3.2 Difference Circuit

Size	2"x3"x.5" plus external pot.
Potentiometer	20KΩ - 20 turn
Power	+12V @ 10.0A, ±200mV & ±100mA +12V @ 10.0A, ±200mV & ±100mA
Input	0.0-3.6V
Output	Input-1.800V, ±1mV

2.2 Specifications for COTS Electronics

2.2.1 Introduction

As stated before, it is better to buy parts that are proven and easily attainable. This section covers those electronic components that are available commercially off the shelf.

2.2.2 Specification List

2.2.2.1 Servo Amplifier

Size	2.98”x5.09”x.99”
Weight	10oz
Power	20-80VDC
Peak Current	±12A
Bandwidth	2.5KHz
Temperature	-25°C to 65°C

2.2.2.2 Voltmeter

Size	1.5”x4”x5” (max.)
Power	120VAC, 60Hz, 2.5W
Range	±20VDC
Accuracy	±.05% 3 digit
Temperature	0 to 50°C

2.2.2.3 Power Supply

Size	5"x5"x11"
Weight	12lbs (max.)
Input Power	84-264 VAC, 47-440Hz
Output	28VDC @ 9A 10VDC @ 10A 10VDC @ 10 A
Ripple	.1% of 10mV RMS 1% or 5mV peak-to-peak

2.2.2.4 Satellite Velocity Tachometer

Size	2.5"D x 1"H (max.)
Weight	3.2oz
Output	16V/1000RPM
Supply Power	5.5-16 VDC (typical 12 VDC)
Supply Current	.6mA
Shaft Speed	10,000 rpm (max. continuous)

For further details see Appendix C.

3.0 Design Summary

3.1 Design Process

SADSaC will be designed to meet specifications in the most efficient, cost-effective manner possible. Many items and activities will be done concurrently, with completion dates being the same. For example, all parts should arrive at the same time any internal circuits are finished so complete wiring can be done at once. The process will begin with designing the skeleton (See Section 3.4), while parts are ordered. The skeleton will then be built while parts are coming in and circuitry designed. All parts will then be mounted and wired appropriately, followed by a rigorous testing period where the proper functioning of the system is ensured. With a functioning system, mathematical modeling of the existing system will begin.

Mathematical modeling consists of looking at the system with respect to the dynamics and equations of motion. This takes into account all of the expected disturbances, the output of the sensors and anything affecting the system such as the moment of inertias. The mathematical modeling process is covered in section 6.0.

Once a model is found, it must be verified. The transfer function of the model is computer simulated using MATLAB and compared to the actual responses of the system. A frequency response is obtained by observing the reaction of the system while it experiences a wide range of frequencies. Items specifically needed are the gain and phase at each frequency. A transfer function can be obtained from the frequency response and, again using MATLAB, the step response can be found and compared to the model. The model should match the actual response of the system.

The transfer function is important, because it shows how the system will react to certain inputs, as well as the zero and pole for the system. Now that the zero and pole are known, the controller can be designed. For example, the PI controller, see Figure 3.1.1 below, (More detail Section 7.1.1), cancels out the zero and pole of the motor transfer function, leaving only the gain of the motor system. All of the information is placed in on a block diagram, so the final controllers can be built and tested. If the controller meets the specs the project is finished.

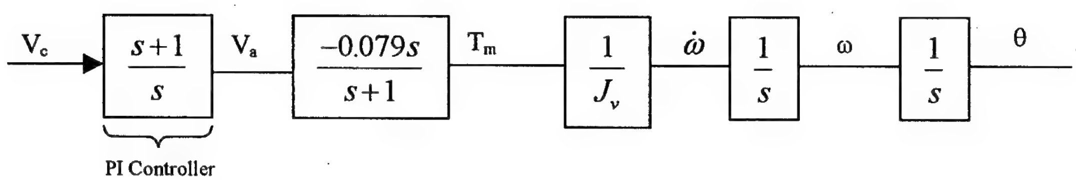


Figure 3.1.1: Function block diagram with PI controller.

3.2 Wiring Diagram

3.2.1 Wiring Diagram for Satellite

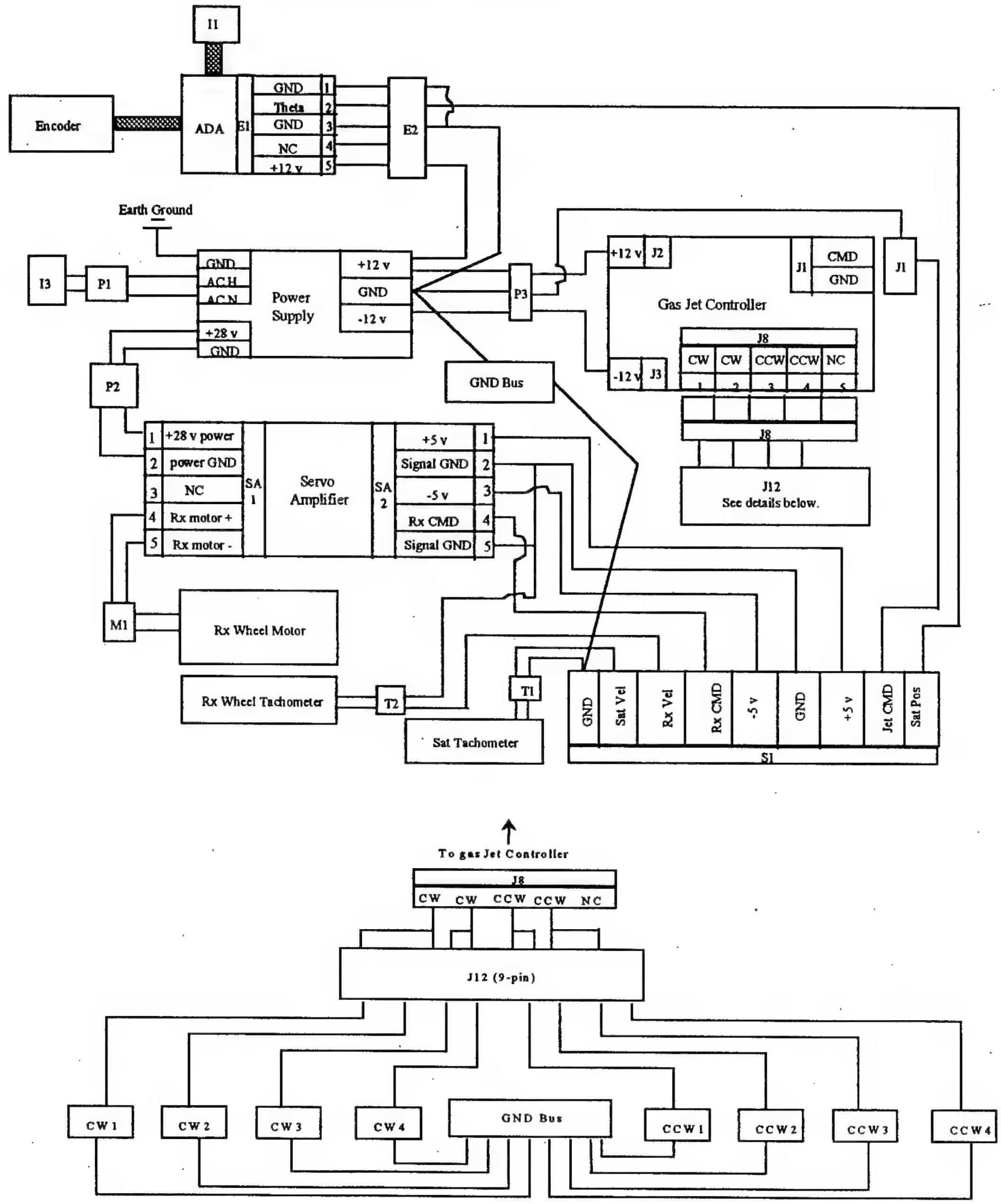
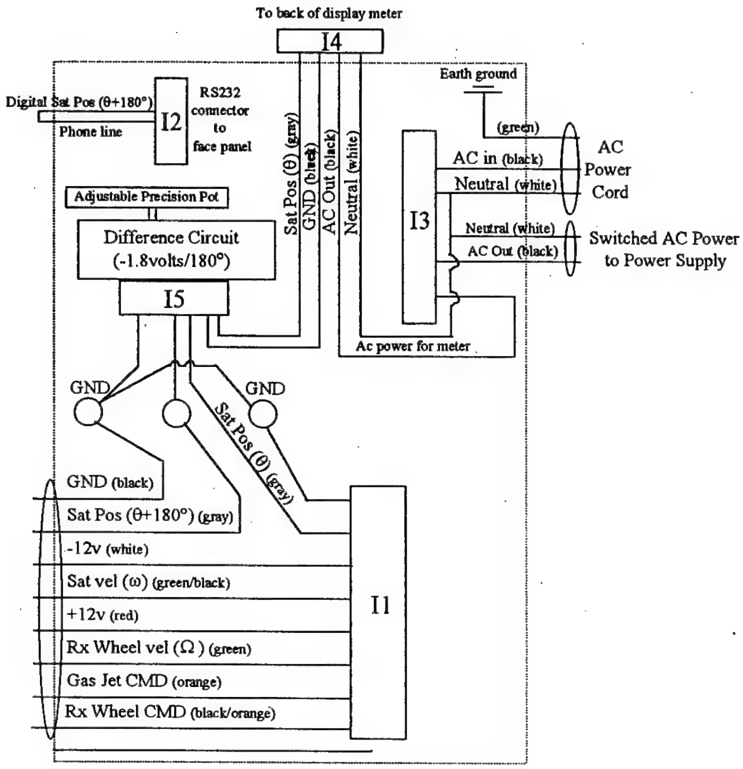
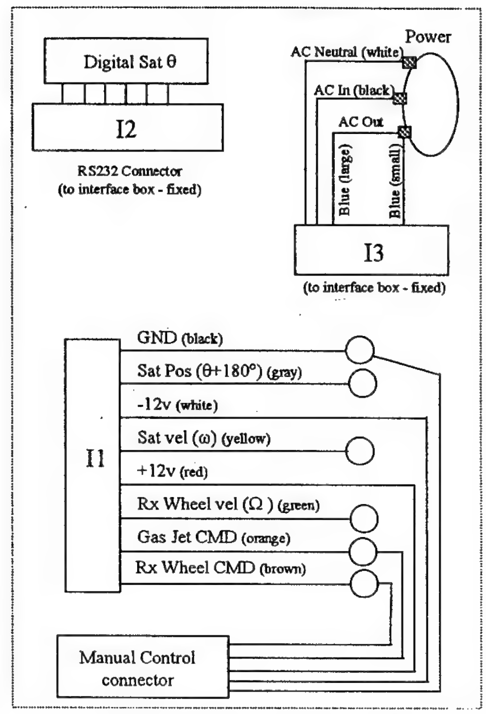


Figure 3.2.1.1: SADSaC wiring Diagram. Shows the interconnection of electronic components located in Figure 3.4.1.1.

3.2.2 Interface Box



Fixed Portion Wiring



Removable Face Panel Wiring

Figure 3.2.2.1: Interface Box Wiring. The interface box is where all internal signals are accessible through the face of the box. The Oval to the left are the lines coming out of the pipe (Figure 3.4.1.1) into the box.

3.3 Designed Circuits' Schematics

3.3.1 Gas Jet Controller

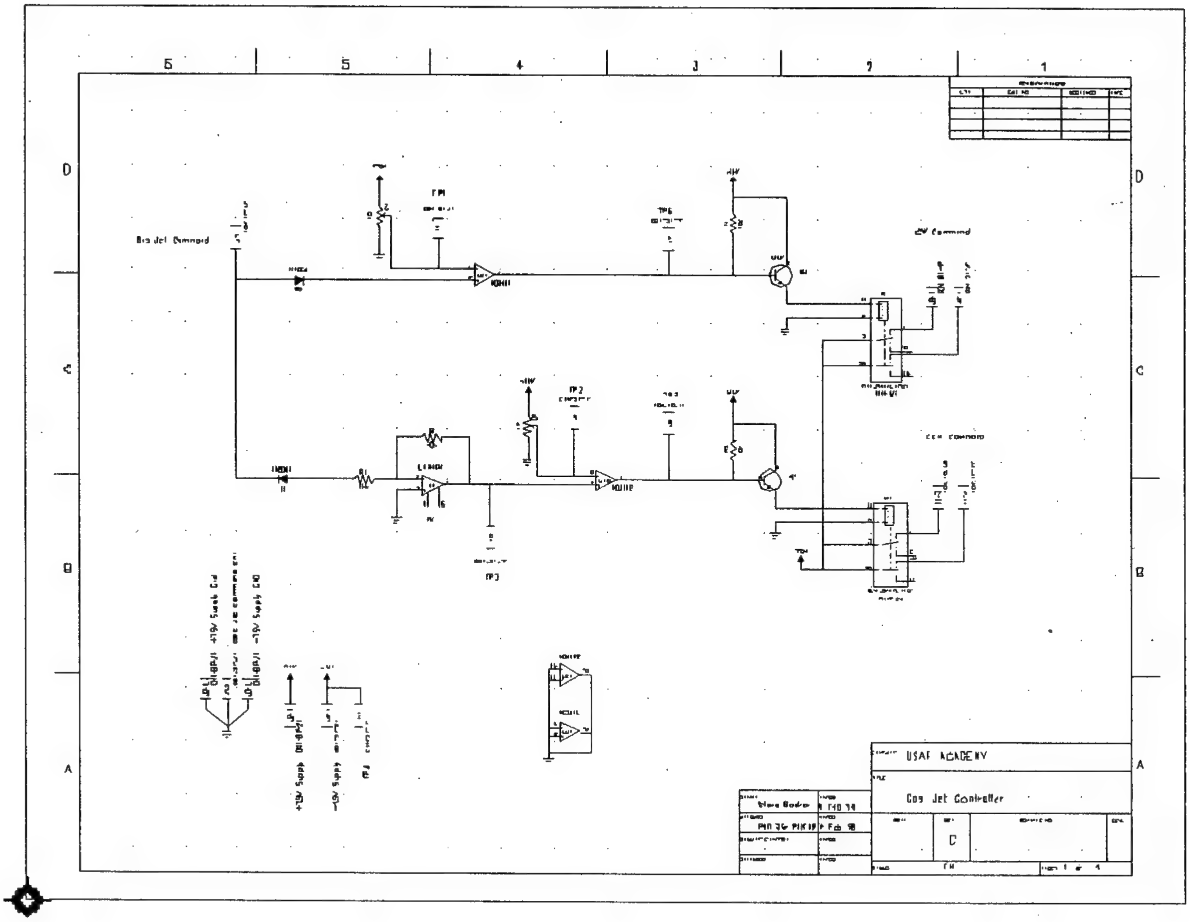


Figure 3.3.1.1 Schematic of circuit that fires the gas jets on command.

3.3.2 Differencing Circuit

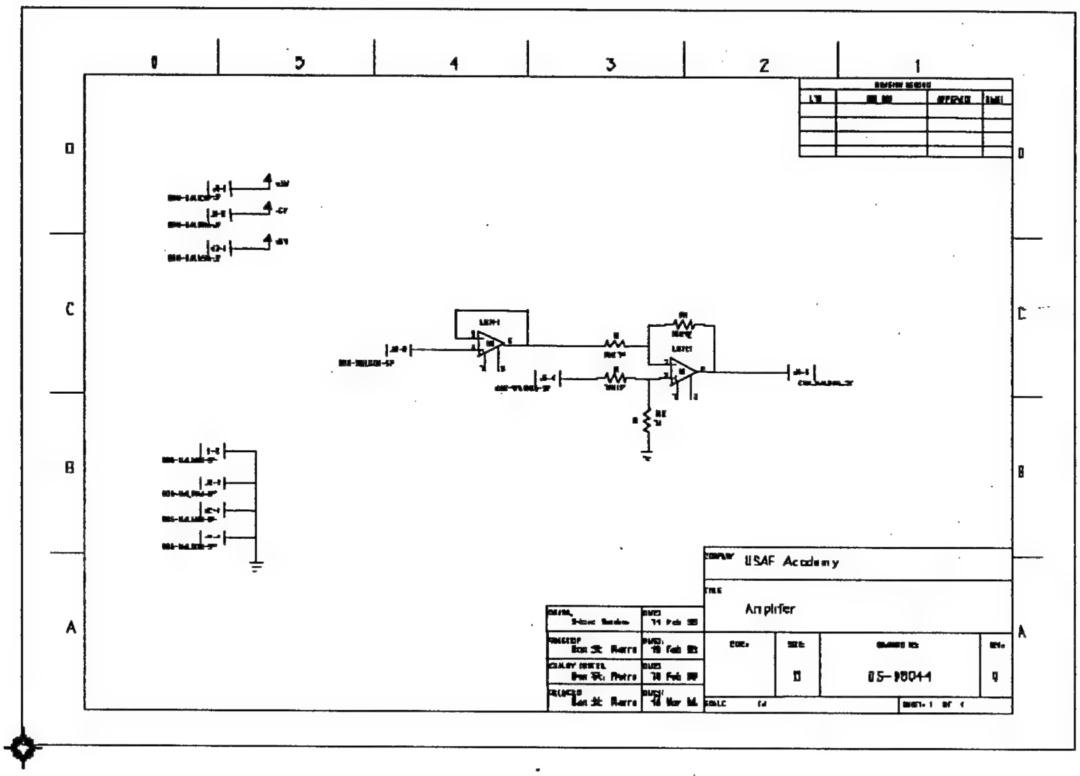


Figure 3.3.2.1: Schematic for differencing circuit. Subtracts 1.800v from the satellite position signal

3.4 Skeletal Design

3.4.1 Satellite Stand

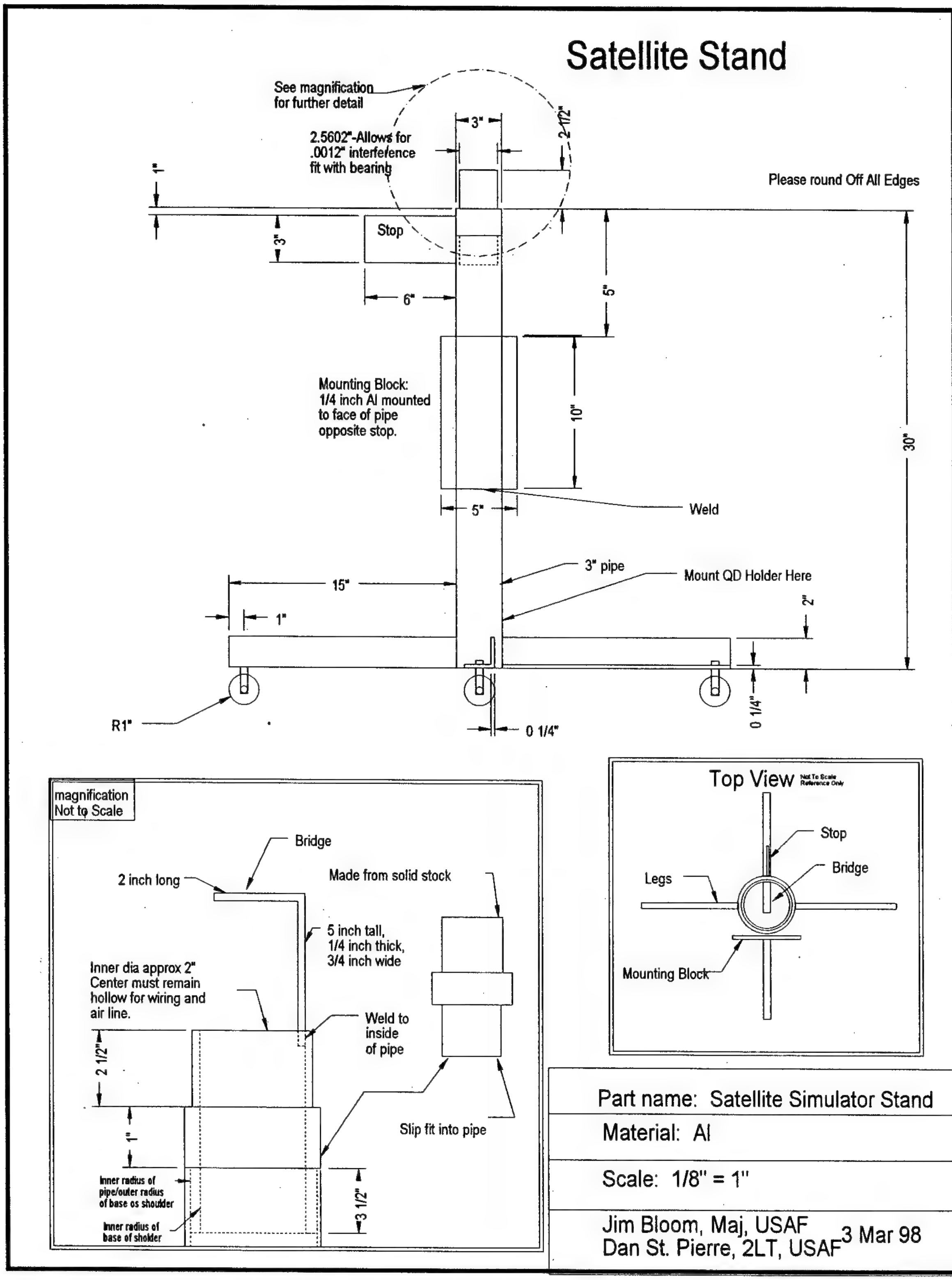


Figure 3.4.1.1: Satellite Stand. Base for SADSaC provides support and mobility. It also contains a surface to mount an interface and a mechanical stop.

□□□□□□□ 3.4.2 Satellite **Structure**

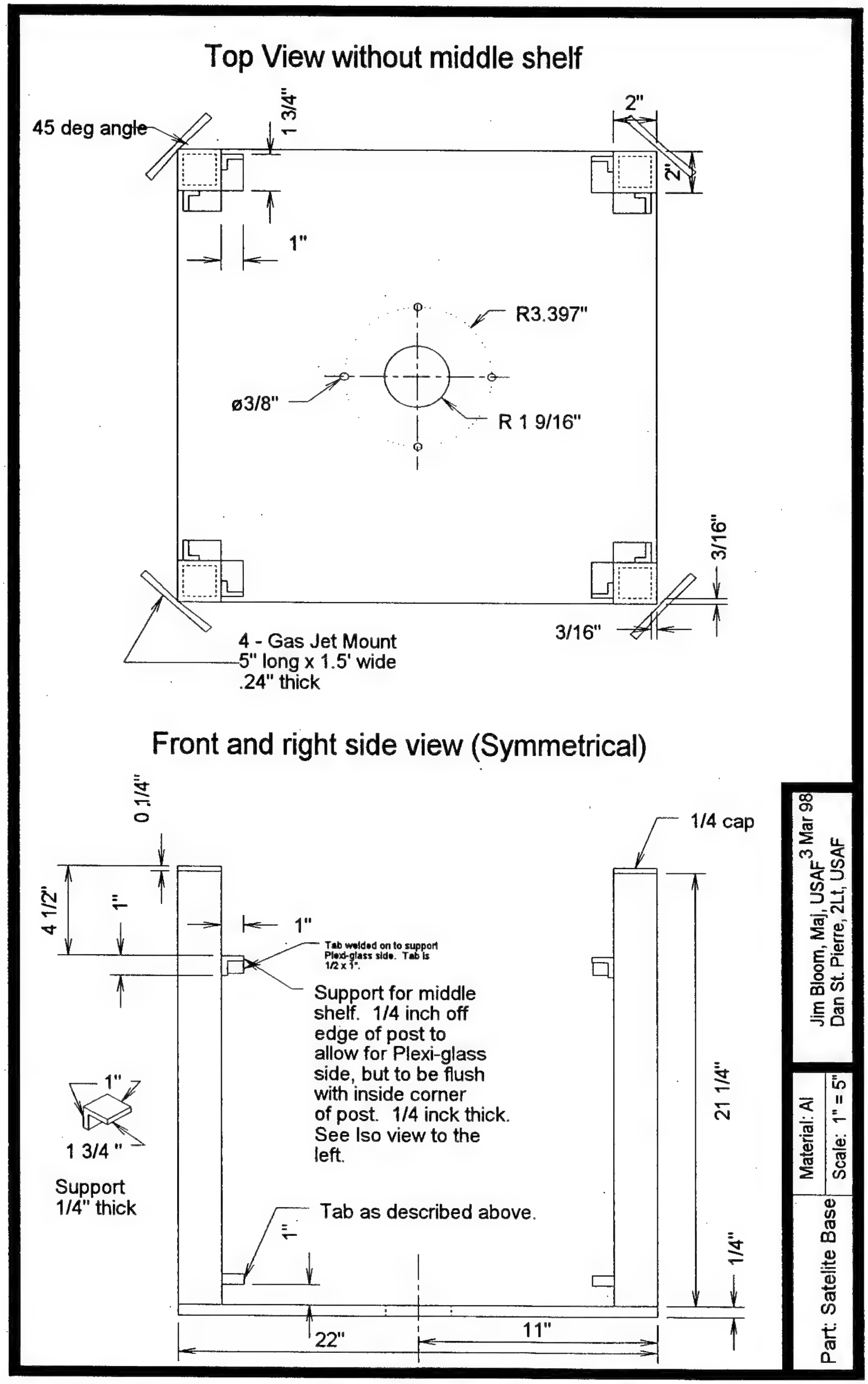


Figure 3.4.2.1: Main section for satellite structure. This figure shows the dimensions of the satellite structure, the gas jet mounts, and the tabs for plexi-glass attachments.

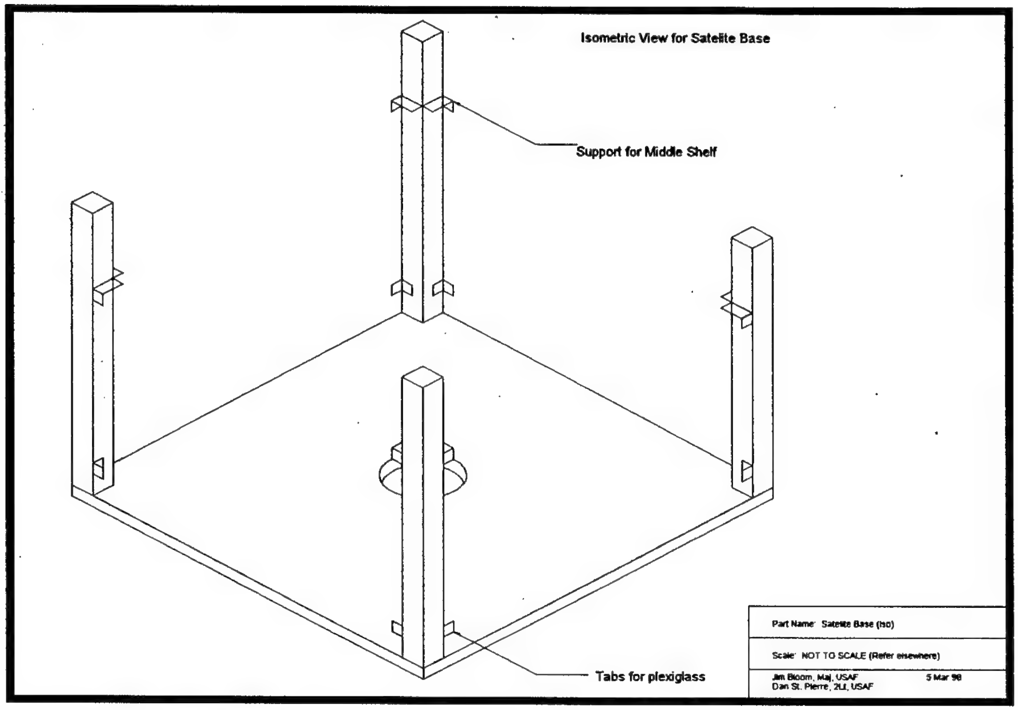


Figure 3.4.2.1: isometric view of satellite structure. This better demonstrates the shape.

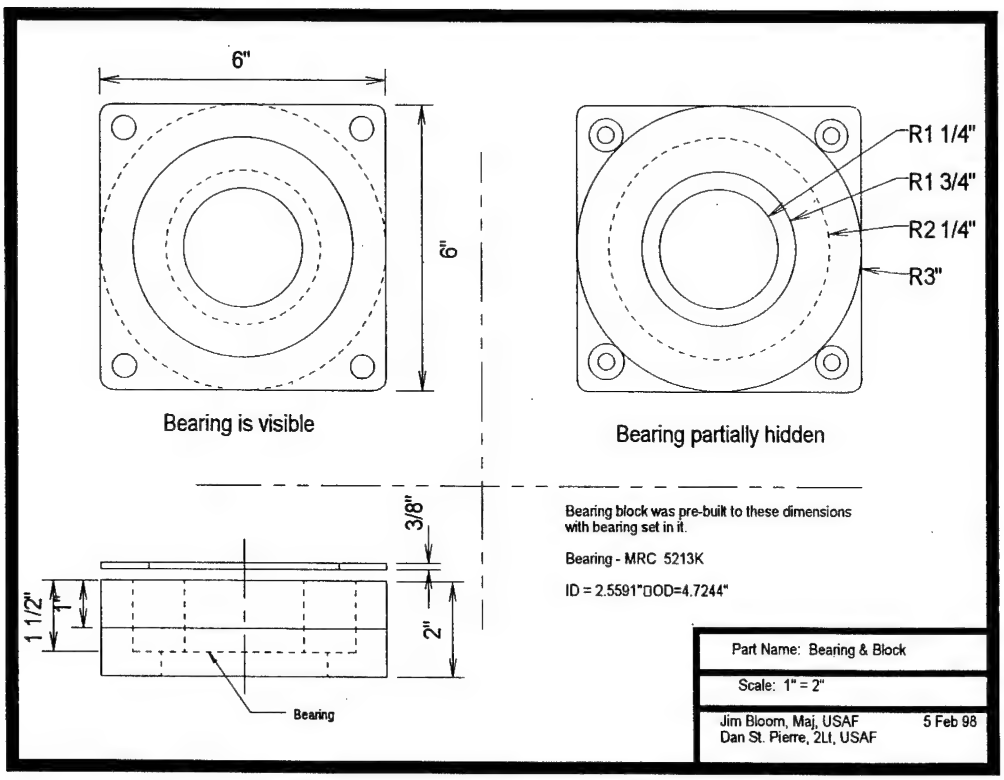


Figure 3.4.2.3: Ball bearing and block. Shows the bearing and its mounting block. Holes correspond to those in figure 3.4.2.1. The bearing also has an interference fit to the satellite stand (Figure 3.4.1.1)

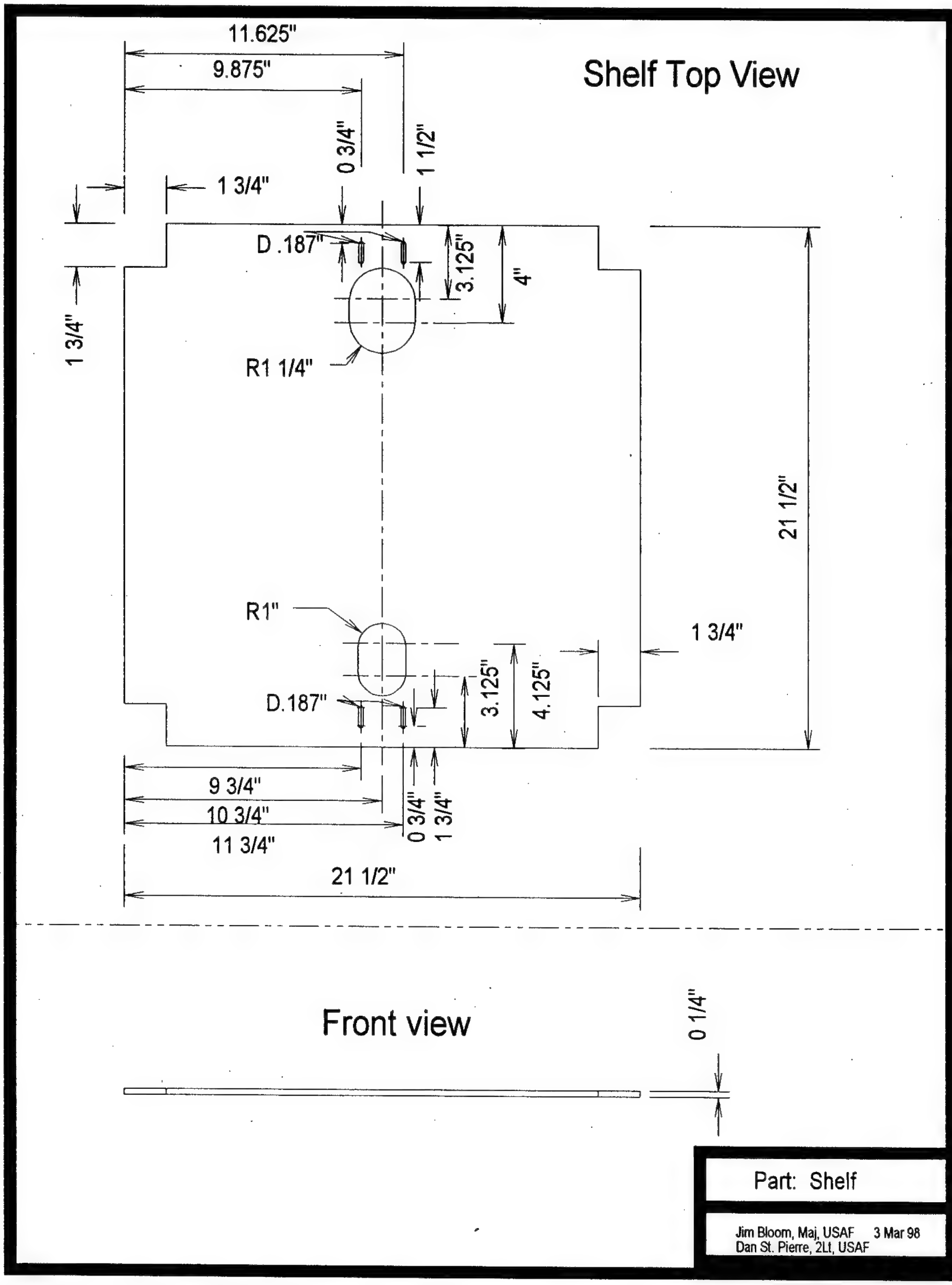


Figure 3.4.2.4: Middle Shelf. Provides support for the reaction wheel, the motor, tachometer and optical encoder bracket.

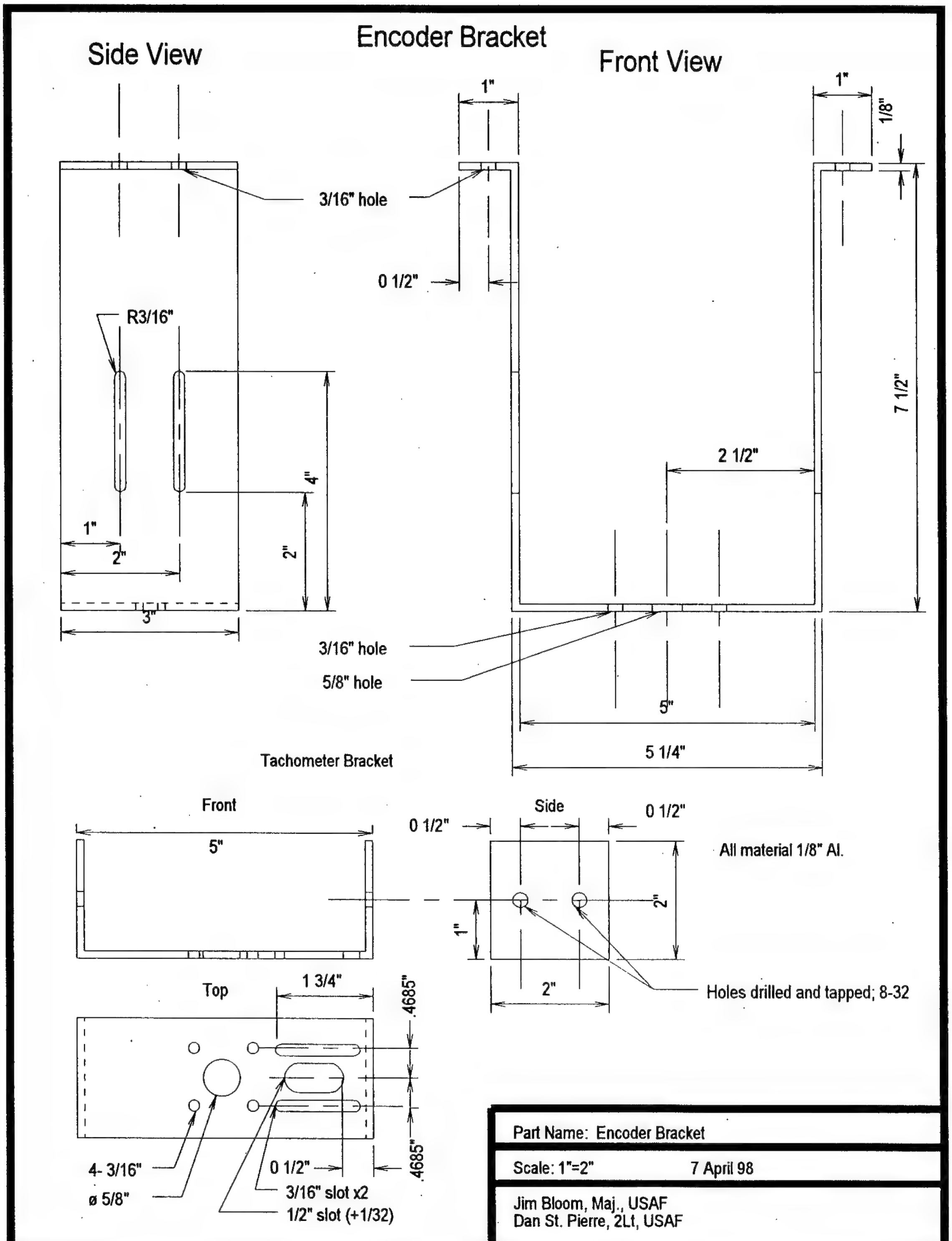


Figure 3.4.2.5: Encoder Bracket. Tachometer bracket fits into encoder bracket to hold the absolute optical encoder and the position tachometer the bottom to the middle shelf (Figure 3.4.2.4)

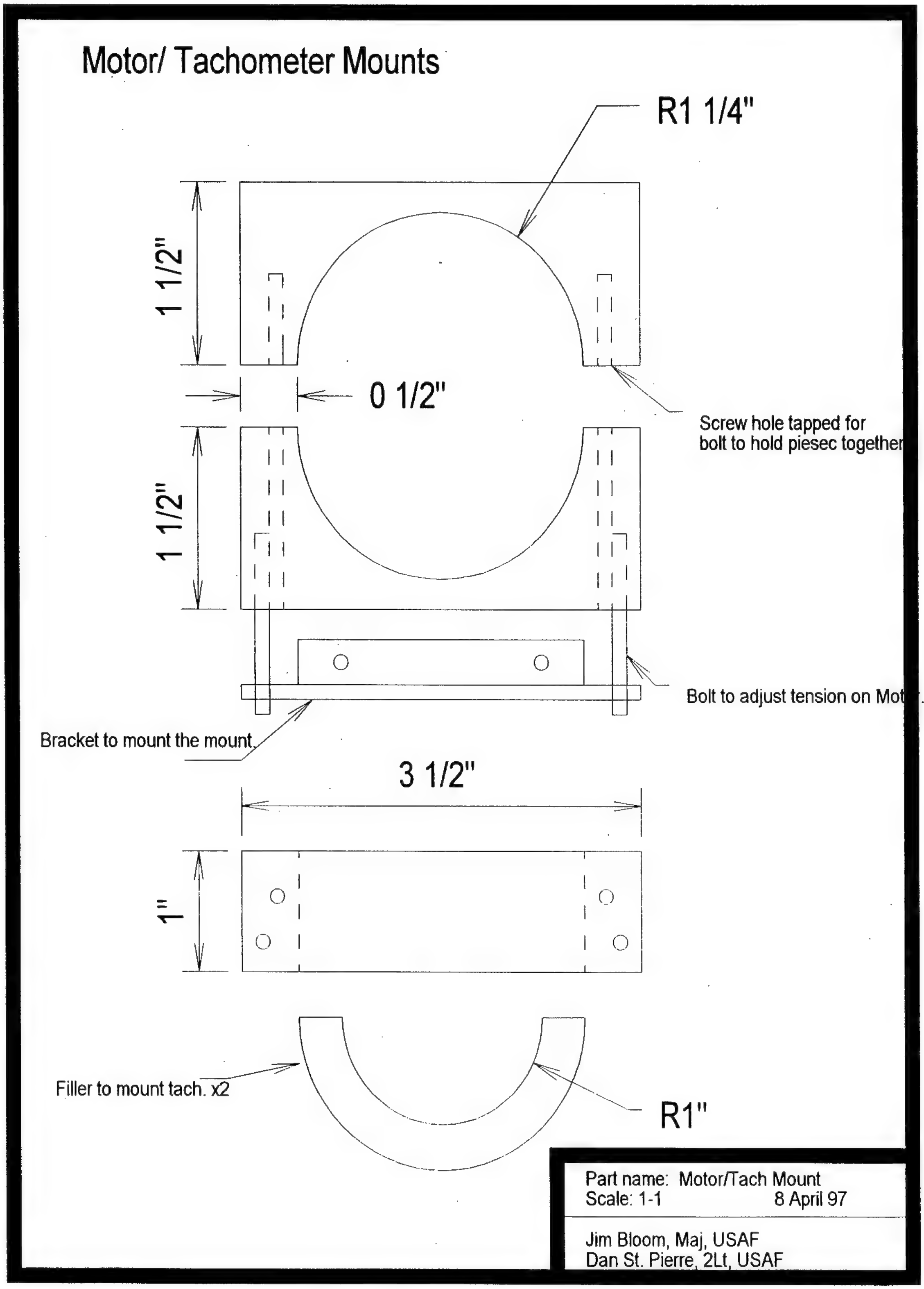


Figure 3.4.2.6: Motor/Tach Mounts. Blocks hold the motor in the middle shelf (Figure 3.4.2.4) in an upright position to drive the reaction wheel. Since the tach is smaller the filler is used.

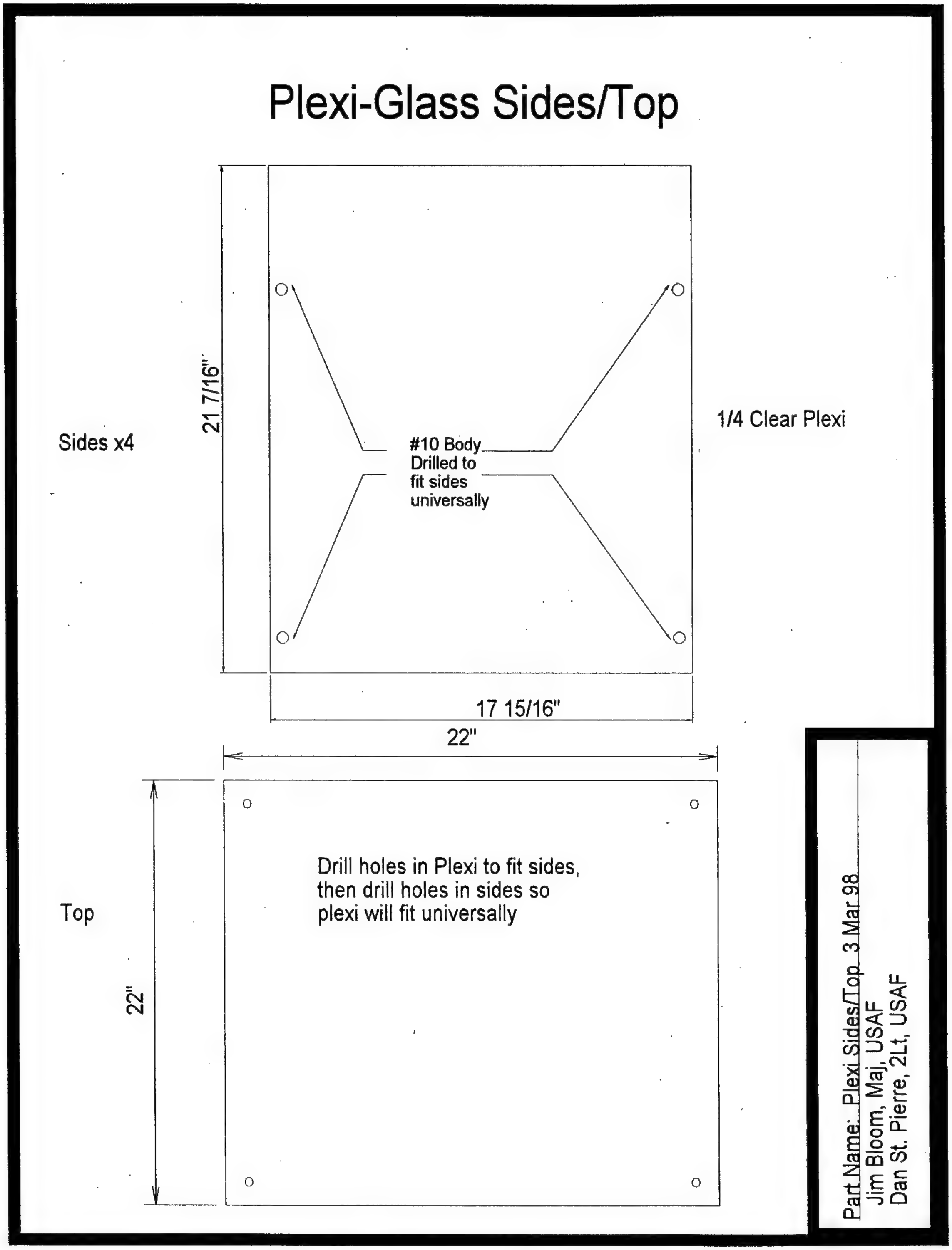


Figure 3.4.2.7: Plexi-glass Sides provides protection and allows for visibility to the internal equipment. The holes fit to the tabs in Figure 3.4.2.1

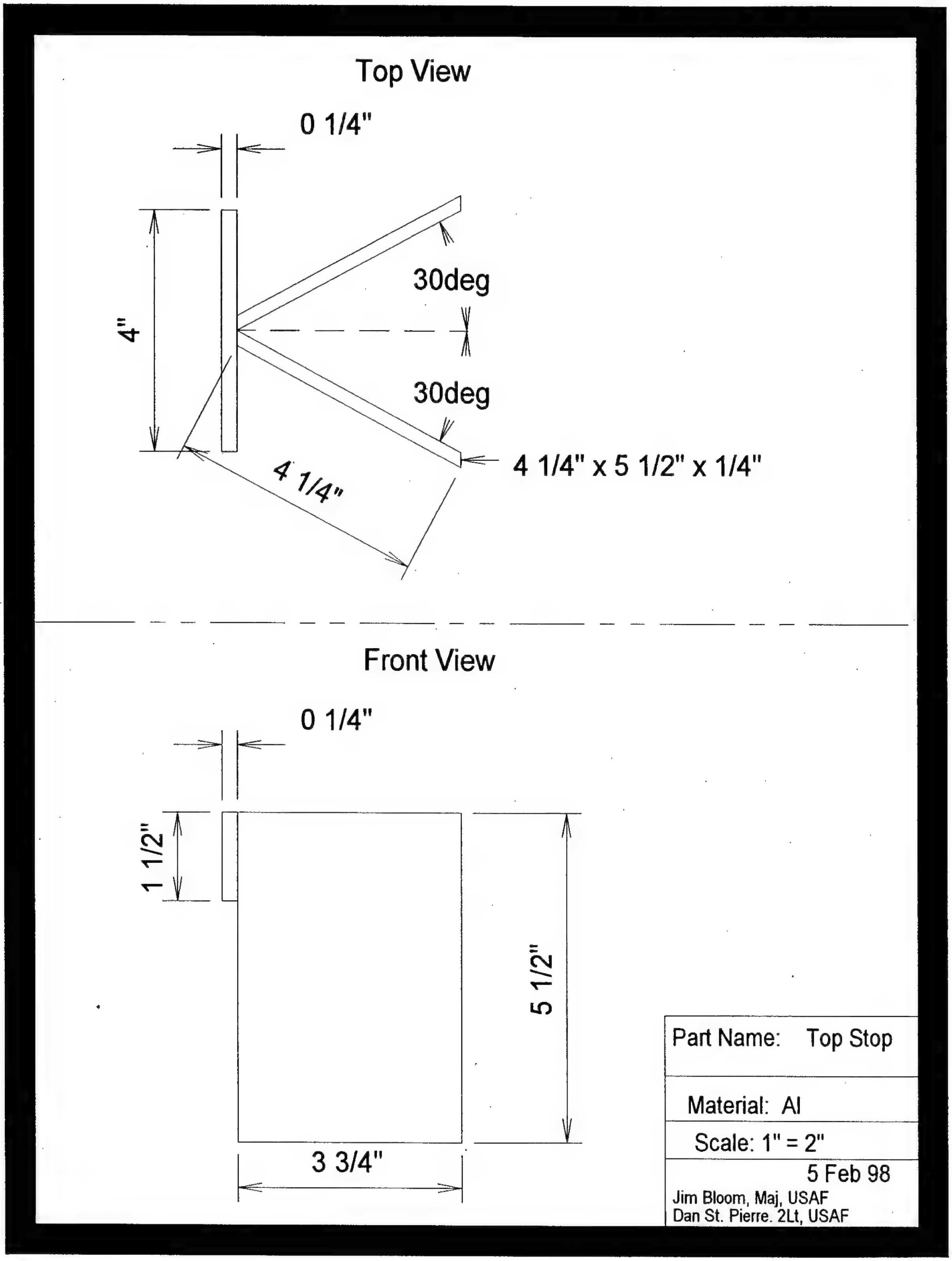


Figure 3.4.2.7: Satellite Mounted Mechanical Stop. The stop prohibits 60° of motion for the satellite. This allows for a total of 300° rotation.

3.4.3 Reaction Wheel

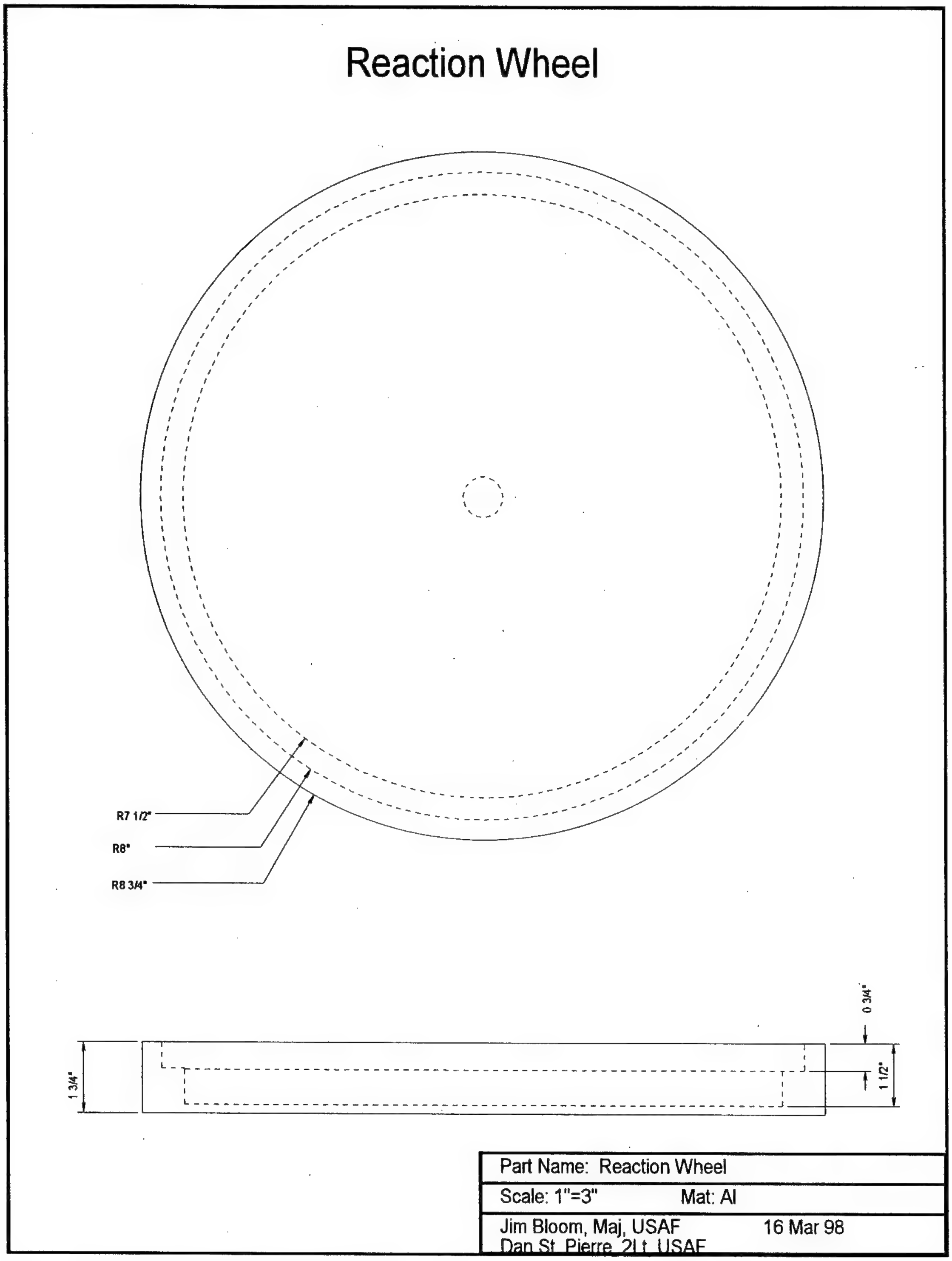


Figure 3.4.3.1: reaction Wheel

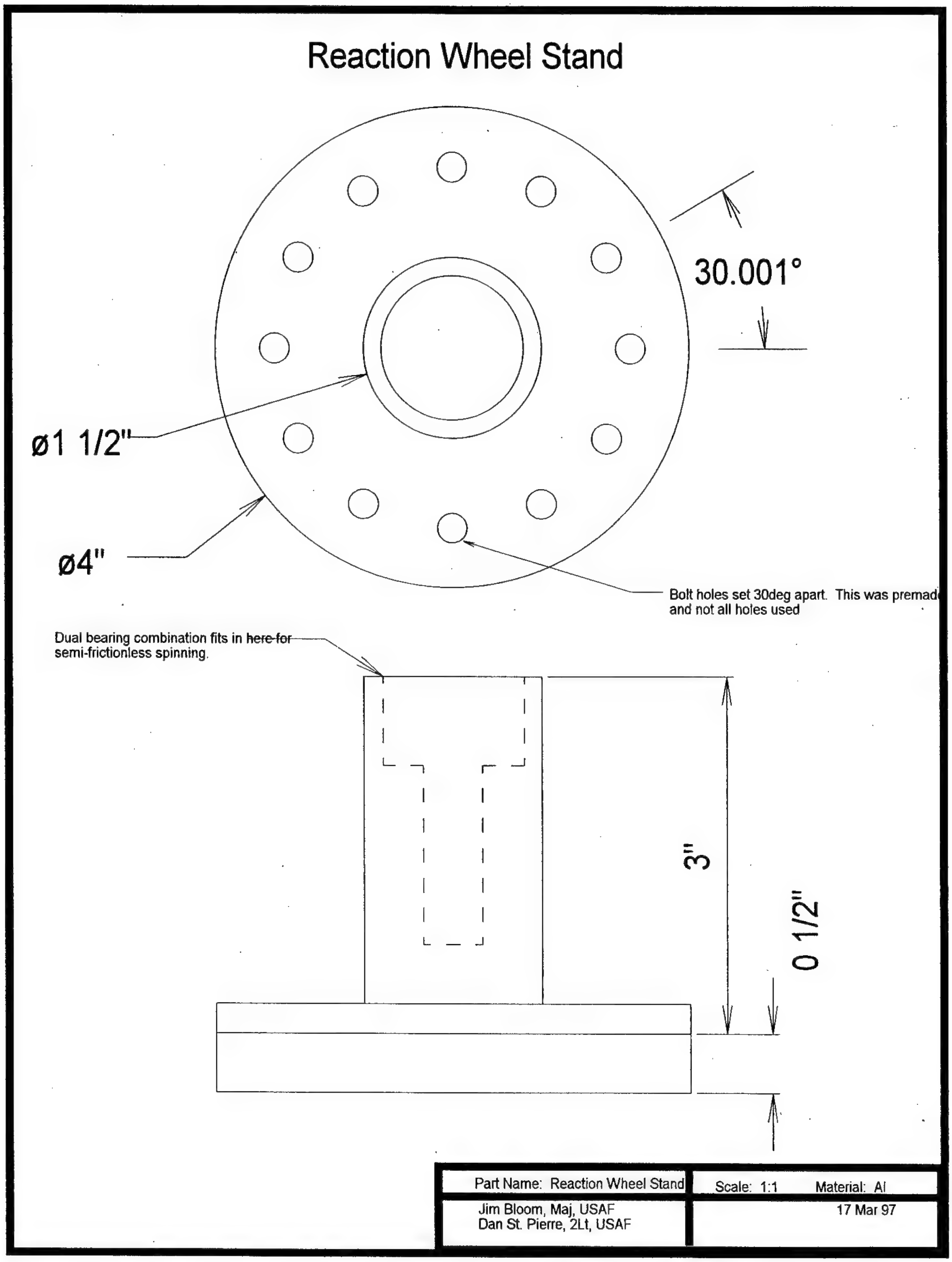


Figure 3.4.3.1: reaction Wheel Mount. Mount holds reaction wheel above surface and contains a dual bearing system allowing for near-frictionless movement of the wheel.

3.4.4 Airline Mounts

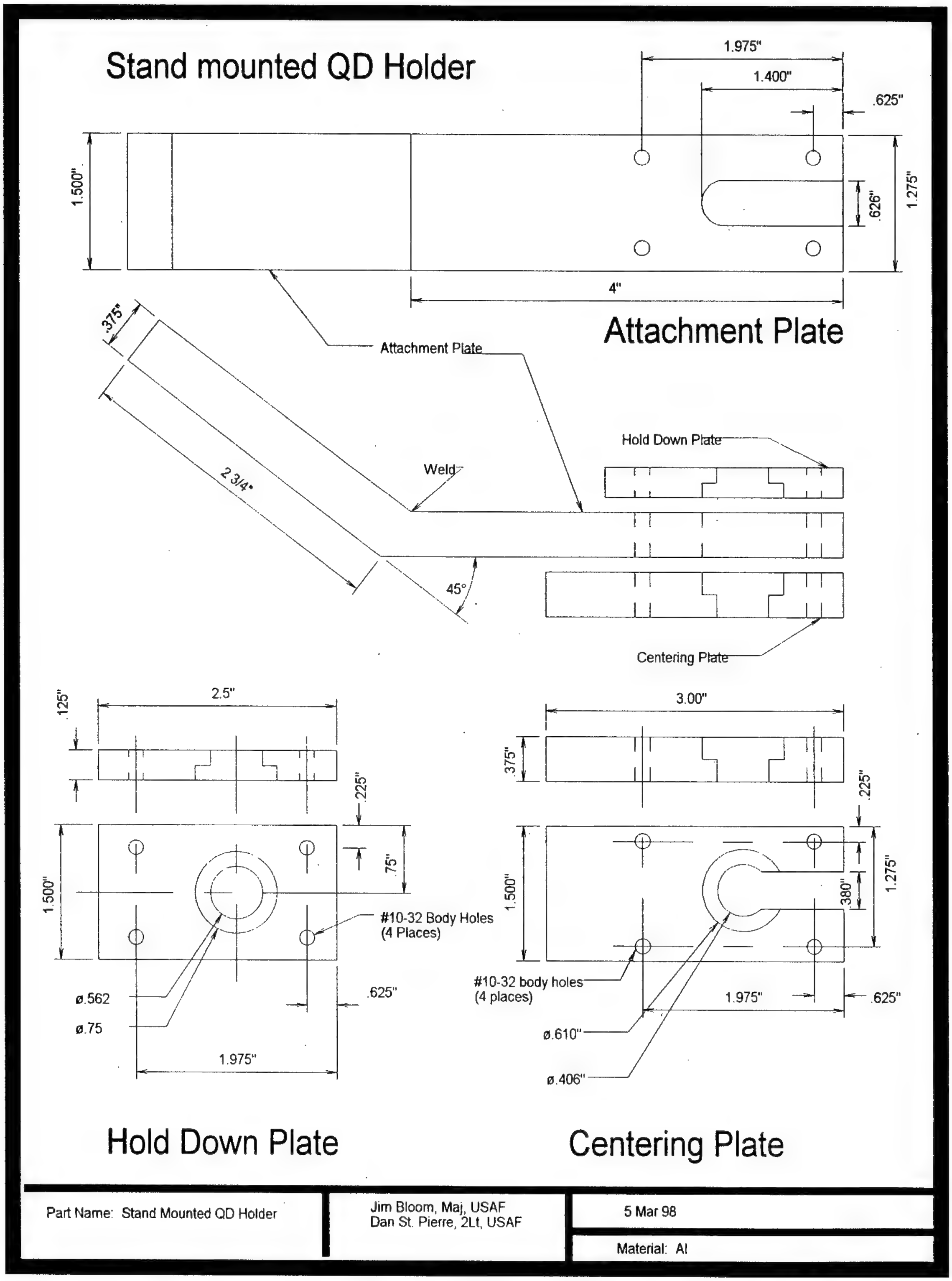
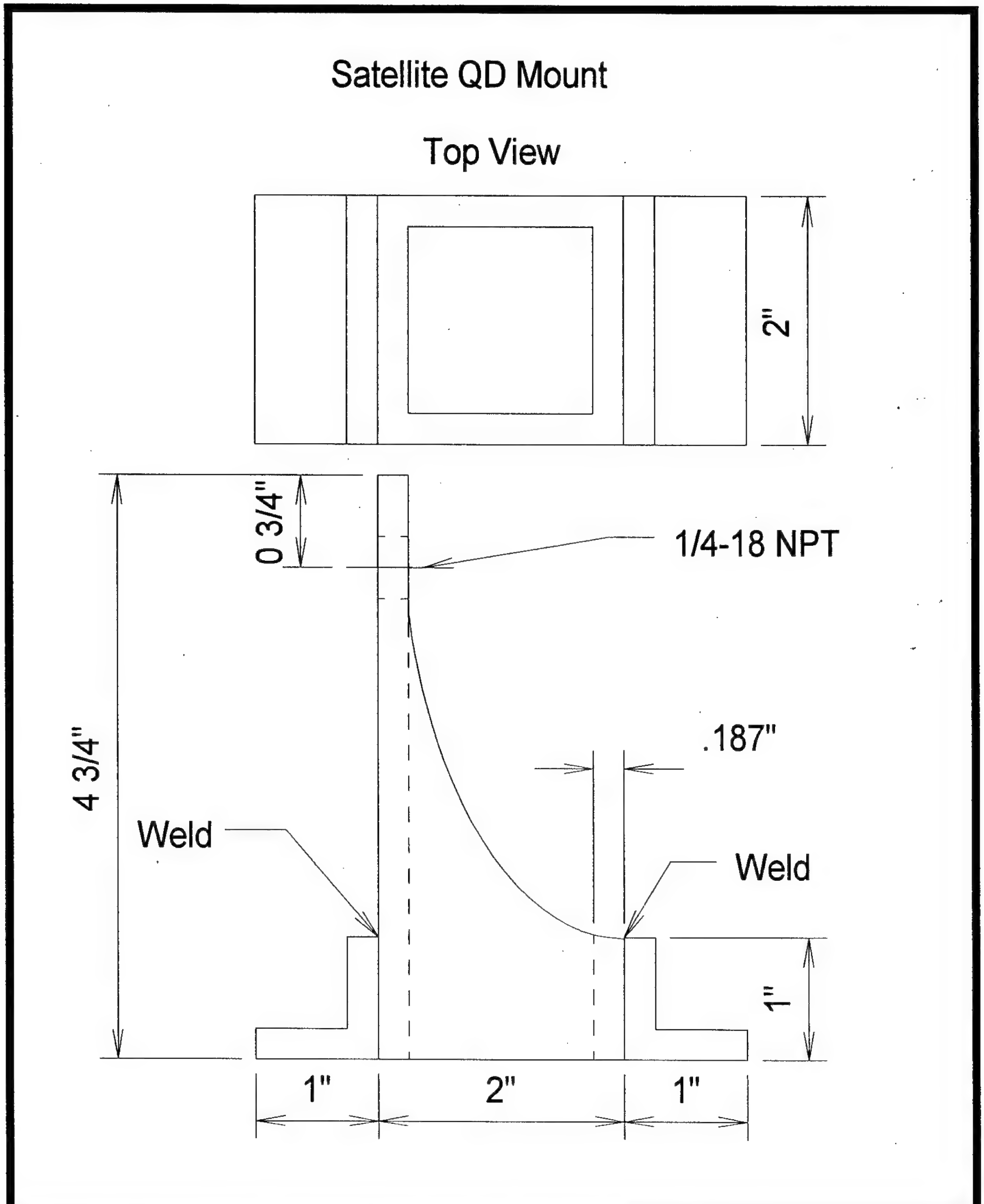


Figure 3.4.4.1: Stand mounted Quick Disconnect holder. This is welded to the stand (Figure 3.4.1.1) and provides a solid mount for the airline running up the pipe.



Part Name: Satellite QD Mount	Jim Bloom, Maj, USAF Dan St. Pierre, 2LT, USAF	5 Mar 98	Material: Al

Figure 3.4.4.2: Satellite Mounted Quick Disconnect Holder. Mounted in the satellite structure, this provides a solid hold for the airline coming out of the pipe.

4.0 Activity Plan

4.1 Overview

In order to accomplish this design in the most efficient manner, an activity plan has been set up with all expected procedures listed. This is necessary to stay on track during the design and ensure all activities are accomplished in a timely manner. This also helps to determine a proper timeline in which the activities will be accomplished so one piece does not hold up the rest of the design if it could have been done concurrently. For example, ordering the unavailable parts while the frame is being built.

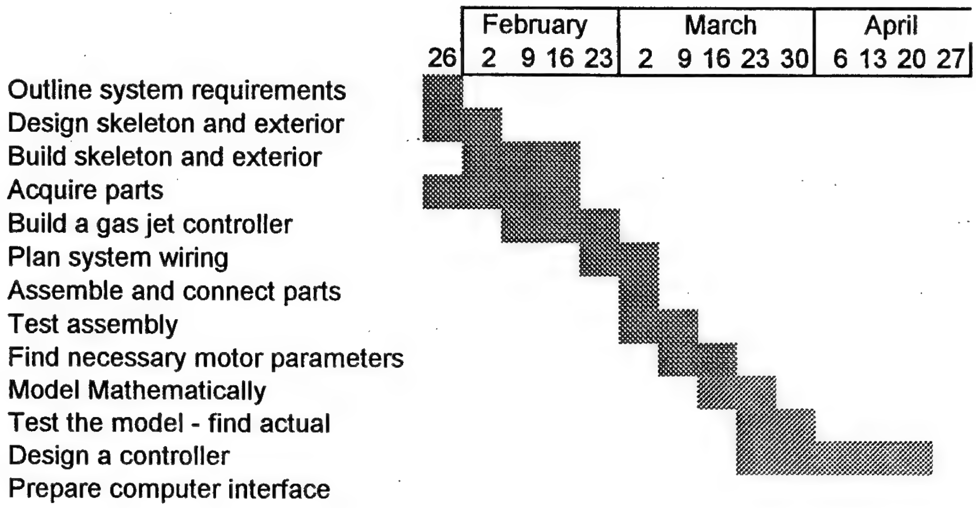
? Schedule

4.2 List of Activities

- Outline system requirements
- Design SADSaC's skeleton and exterior features
- Build SADSaC's skeleton and exterior features
- Acquire necessary parts either by ordering or setting aside those in hand ?
- Design and build a gas jet controller
- Plan system wiring
- Assemble and connect parts
- Test assembly
- Find necessary motor parameters
- Mathematically model the system
- Test the model - find actual model

- Design a controller for the system
- Prepare computer to interface with the system

4.3 Gant Chart



5.0 System Testing

5.1 Satellite Moment of Inertia

5.1.1 Purpose

The satellite's moment of inertia is a fundamental quantity that must be known in order for any modeling to take place. It has a part in everything driving the system.

5.1.2 Procedure

For this test, the gas jets will be used to apply a constant torque. The thrust applied by the jets varies according to pressure in the airline, so it must be measured beforehand. Apply step torque to the satellite using the gas jets. The thrust can be measured with a spring scale. The torque is the radius arm multiplied by the thrust. Measure the velocity and position of the satellite with respect to time using the strip chart.

5.1.3 Result

Using the equation $\theta(t) = \frac{1}{2} \cdot \frac{T}{J_v} t^2$ and the results from the strip chart (see Appendix), J_v can be solved for using position and time. Likewise, the equation $\omega(t) = \frac{T}{J_v} t$ can yield a J_v value using the angular velocity. T is the torque and is found by multiplying the thrust by the radius out from the bearing. J_v = 2.5 KG-m^2. See Appendix D for Data.

5.2 Reaction Wheel Tachometer Calibration

5.2.1 Purpose

Since the tachometer being used is a pre-existing component and has no documentation, the volt to rpm ratio must be found in order to measure the wheel speed.

5.2.2 Procedure

Since the volt to rpm ratio is needed, all that the test consists of is a time measurement and the amount of turns in that time, along with the output of the tachometer at that speed. For convenience a yellow tab is placed on the wheel for easier counting. Two trials will be done to eliminate human error. Actual counting of the revolutions can only be done at low speeds, so a strobe light will be used to measure the frequency at higher rates by timing the strobes to keep the yellow tab on the wheel stationary. When this occurred the frequency of the strobe equals some integer multiple of the wheel.

5.2.3 Results

5.2.3.1 Low Speed Tests

The results for the low speed tests are as follows:

Input Voltage (V)	# of Revs	Time (seconds)	Tach voltage (V)
2.44	22	18.67	2.75
2.44	24	19.73	2.76

Table 5.2.3.1: Results of low speed tachometer calibration tests.

Results of the first trial are;

$$\frac{22revs}{18.67\sec} = 1.18\frac{revs}{\sec} \times 60\frac{\sec}{\min} = 10.7rpm$$

And the results of the second trial are:

$$\frac{24revs}{19.73\sec} = 1.22\frac{revs}{\sec} \times 60\frac{\sec}{\min} = 73rpm$$

The average of the two trials is 71.9rpm. To find the ratio of volts per rpm, divide the number of volts by total rpm.

$$\frac{2.75volts}{71.9rpm} = 0.038\frac{volts}{rpm}$$

5.2.3.2 High Speed Tests

The table below shows the results to the strobe light tests.

Strobe Frequency (rpm)	Multiple	Actual Frequency (rpm)	Tachometer Voltage (V)	Total rpm
428	3	142.7	5.3	0.037
426	3	142	5.25	0.037

Table 5.2.3.2: Test results using strobe light for frequency.

In this case the second trial was run in the opposite direction to verify that the tachometer did not have a bias voltage.

Using the three values for the tachometer, and taking an average yields a tachometer reading of 0.037 volts/rpm.

5.3 Motor Parameters

5.3.1 Purpose

As with the tachometer, this is a generic DC brushed motor. It is therefore necessary to find certain parameters, mainly A and B for the mathematical model

($B = \frac{J_w}{\tau_m}$ and $A = \left.\frac{\Omega_{ss}}{V_a}\right|_{avg} \times B$). The purpose of testing the motor parameters is to find values needed in the mathematical model relating to the motor.

5.3.2 Procedure

The time constant, τ_m, is defined as the time it takes for a system to reach 63% of its steady state value given a step input. (See Appendix D) To find this value, apply a step input into the motor and time the response using a strip chart connected to both the output of the motor and the input signal. When this is finished, find τ_m from the results.

5.3.3 Result

Four tests were run on this motor with different step inputs. To eliminate error the average value was taken. The following table lists the obtained values.

Step Input, V_a (V)	$V_{\Omega ss}$ (V)	63% $V_{\Omega ss}$	Time, τ_m (seconds)
-3.5	-8.8	-5.54	20.1
-3.01	-5.35	-3.37	15.9
2.96	6.2	3.61	18.6
3.49	9.5	5.99	21

Table 5.3.3.1: Values of Motor Parameter Testing.

The average τ_m = 19sec.

Knowing the moment of inertia of the reaction wheel the parameter B can be calculated.

$$\tau_m = \frac{J_w}{B}$$

B is a necessary quantity in the mathematical model of the system.

J_w = .1816 kg*m^2. Solving for B and substituting in the known values yields:

$$B = \frac{J_w}{\tau_m} = \frac{.1816 kg \cdot m^2}{19 \sec} = 0.0096 \frac{kg \cdot m^2}{s}$$

$$\boxed{B = 0.0096 \frac{kg \cdot m^2}{s}}$$

The other motor parameter A has the following relationship;

$$\frac{\Omega_{ss}}{Va} = \frac{A}{B}$$

Converting the tachometer ratio from .0037volts/rpm to volts/rad/s yields 0.35v/rad/s. Ω_{ss} is obtained by dividing $V_{\Omega ss}$ by the tachometer ratio.

$V_{\Omega ss}$ (V)	Ω_{ss} (rad/s)	Va (V)	Ω_{ss}/V_a (rad/s/V)
-8.8	-25.1	-3.5	7.17
-5.35	-15.3	-3.01	5.08
6.2	17.4	2.96	5.98
9.5	27.1	3.49	7.77

Table 5.3.3.2: Conversions for Ω_{ss}/V_a.

The average Ω_{ss}/V_a is 6.5rad/s/V. Solving for A yields:

$$A = \left. \frac{\Omega_{ss}}{Va} \right|_{avg} \times B = 0.0624 \frac{N \cdot m}{volt}$$

$$\boxed{A = 0.0064 \frac{N \cdot m}{volt}}$$

5.4 Satellite Frequency Response

5.4.1 Purpose

The purpose of obtaining a frequency response of a system is to determine the system's transfer function by plotting the frequency (log scale(rad/sec)) vs. gain (dB) on one plot and frequency (log scale(rad/sec)) vs. phase (deg) on another. With the transfer function, a controller can be designed.

5.4.1 Procedure

With a frequency generator and strip chart, send a wide range of frequencies into the reaction wheel command port. The satellite will respond to the continuously changing amplitude. From the satellite velocity port connect this signal to the strip chart along with the signal from the frequency generator. The signal range was between .0036Hz to 4.00Hz. From the strip chart, compare the waveforms obtaining a phase change from input to output and the gain of the signal from the input to output.

5.4.3 Result

Plotting the results and throwing out obviously bad data yields the following plots .

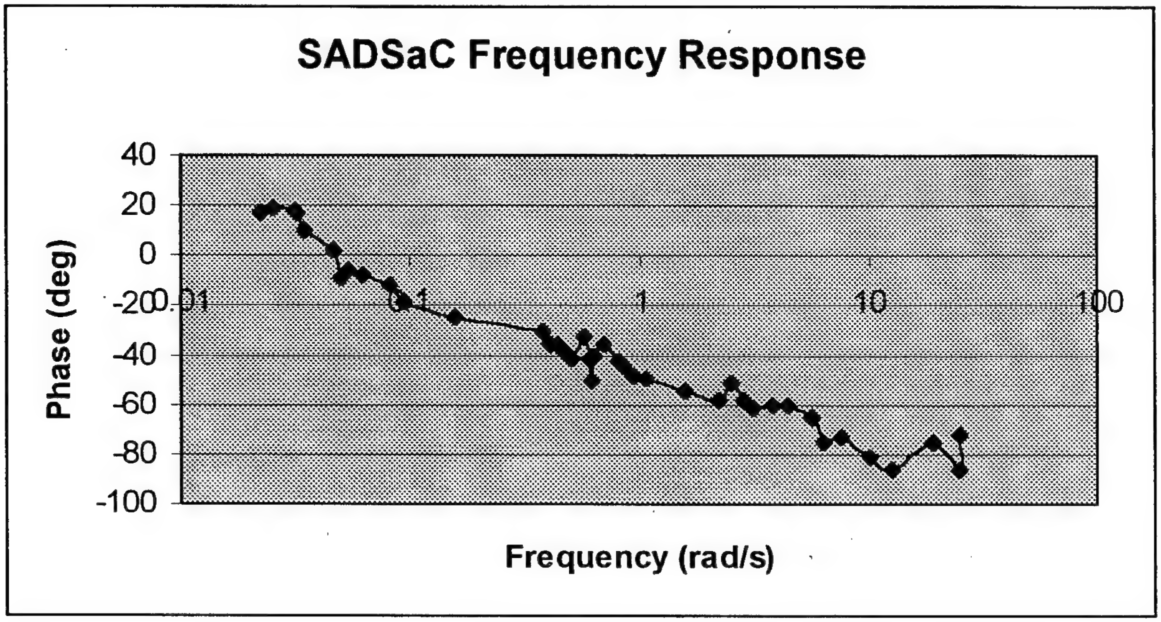


Figure 5.4.3.2: SADSaC frequency response phase plot. This also indicates a corner frequency of 1rad/sec since the plot goes through -45° at this point.

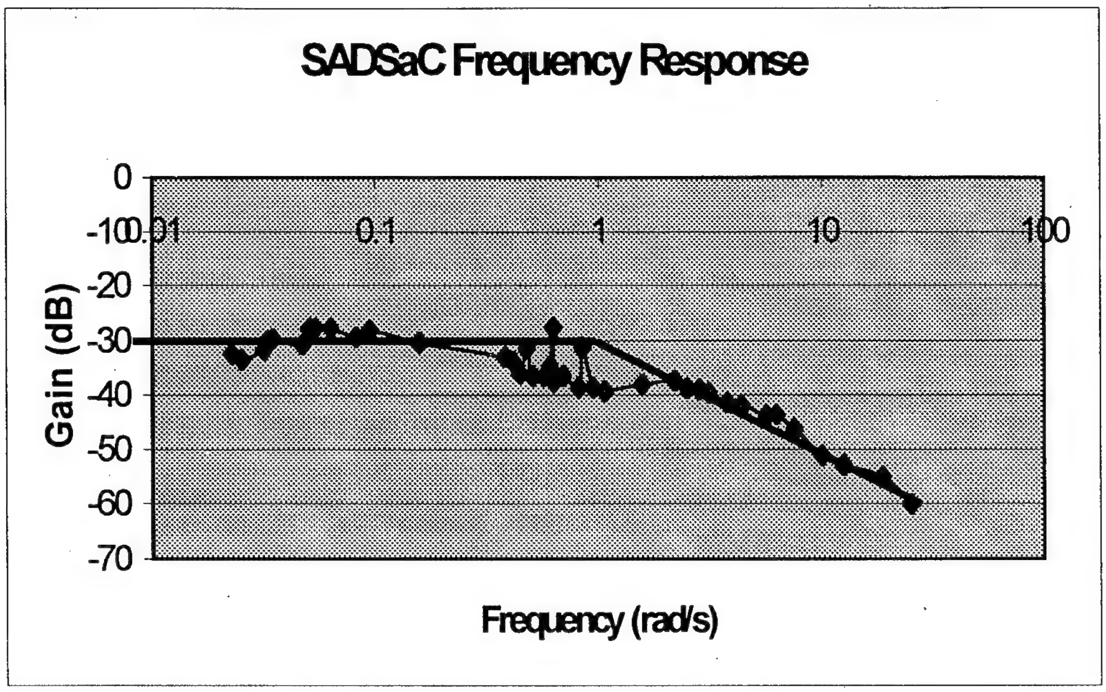


Figure 5.4.3.1: SADSaC frequency response gain plot. This indicates a corner frequency of near 1rad/sec.

The following transfer function can be obtained from these plots:

$$\frac{V_\theta}{V_a} = \frac{0.0316}{s+1}$$

After changing the gain on the servo amplifier, a new transfer function needs to be found. This new function will have the same phase as above with a different gain and is given below

$$\frac{V_\theta}{V_a} = \frac{0.1}{s+1}$$

Plotting the first transfer function on MATLAB yields:

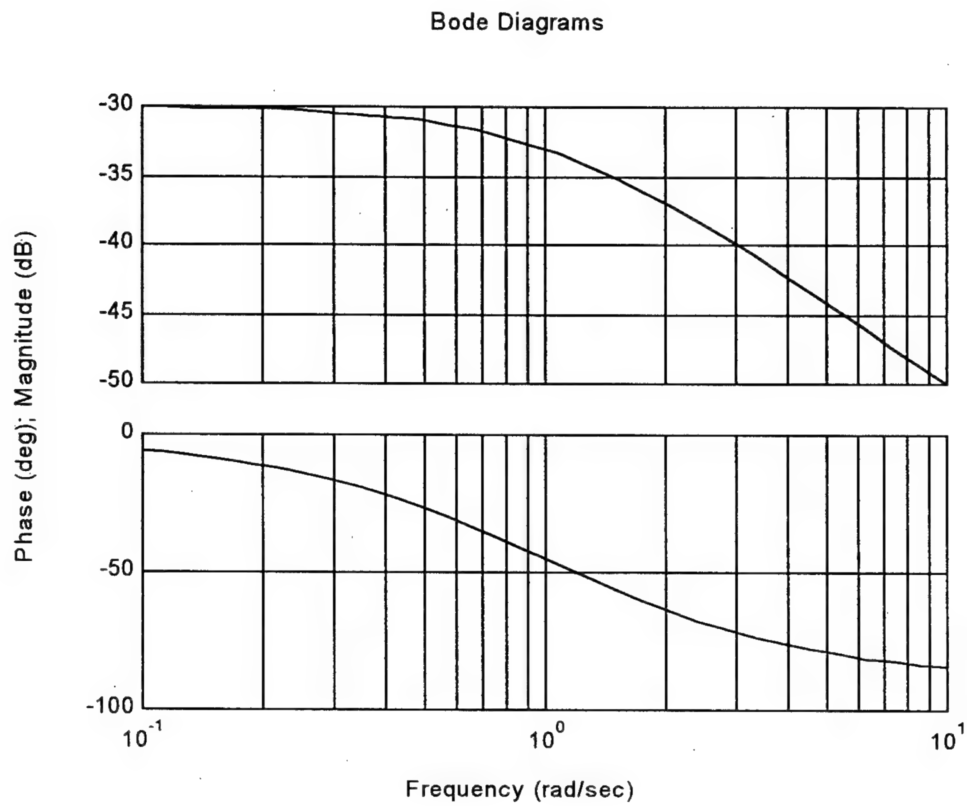


Figure 5.4.3.3: MATLAB Bode plot of equation 5.4.3.1 verifying the transfer function fits Figs. 5.4.3.1 & 5.4.3.2.

5.5 Deadband on Gas Jet Controller Circuit

5.5.1 Purpose

The purpose of finding the deadband and hysteresis is to determine $\pm\delta_1$ and $\pm\delta_2$, which are necessary parameters in the gas jet control scheme.

5.5.2 Procedure

Adjust the positive voltage into the gas jet command line until the jets fire. Record this value as $+\delta_2$. Turn the positive voltage back down until the jets turn off. Record this as $+\delta_1$. Do the same procedure for a negative command. If these values are undesirable, adjust the appropriate potentiometer until it fires at a desirable command.

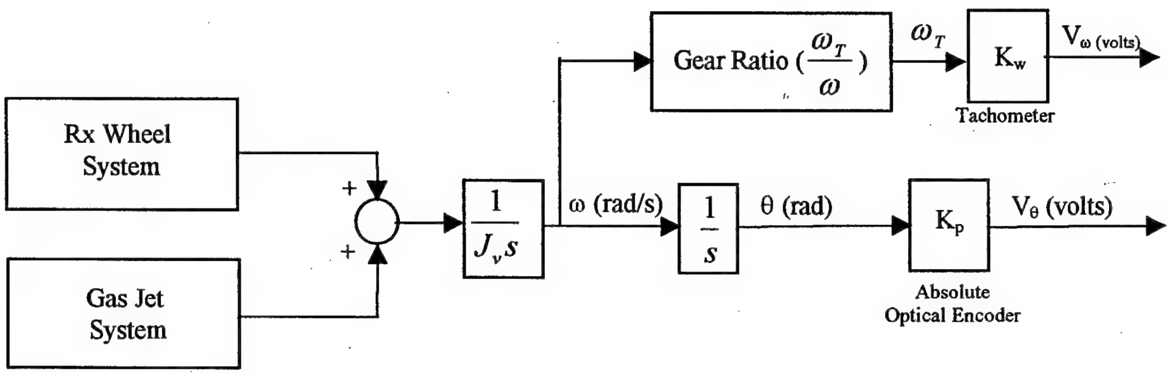
5.5.3 Results

At the time the test was taken, and the controller designed the following values were recorded.

$+\delta_2 = 1.09V$	$+\delta_1 = 1.05V$
$-\delta_2 = -1.08V$	$-\delta_1 = -1.03V$

6.0 Mathematical Modeling

6.1 Overall System Block Diagram



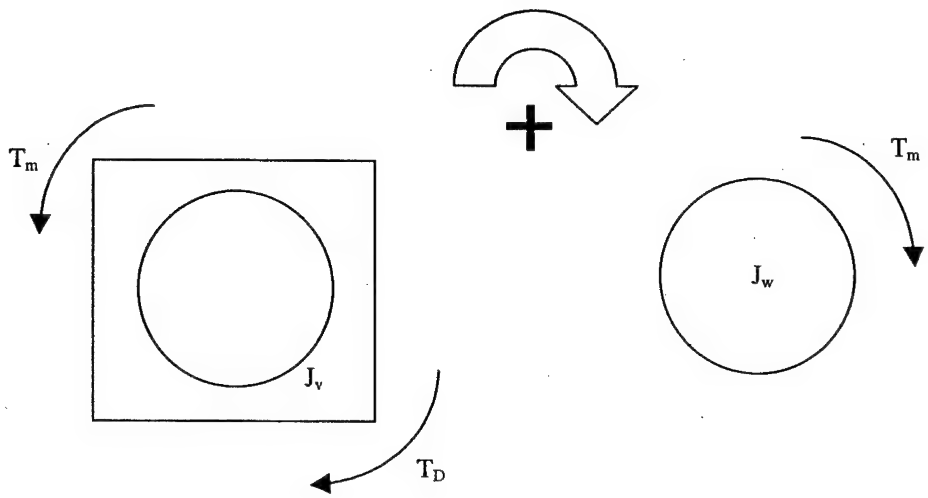
J_v = Inertia of entire vehicle
J_s = Inertia of satellite
J_w = Inertia of wheel
$J_v = J_s + J_w$
ω = Satellite angular velocity
ω_T = Tachometer shaft angular velocity
θ = Satellite angular Position (±180°)

$J_v = 2.5$ kg-m^2
$K_p = 0.0573$v/rad
$K_v = 0.153 \frac{volts}{rev}$
Gear ratio = 3.75
$J_w = 0.1816$Kg-m^2

6.2 System Dynamics

6.2.1 Derivation of Equations

Looking at the entire vehicle and then the wheel separartely, we get the following free – body diagrams:



T_m = motor torque
T_D = disturbance torque

Using $\sum T = J\ddot{\theta}$ with $\Omega =$ Rx wheel angular velocity and $\omega =$ satellite angular velocity

For entire vehicle: $-T_m = J_v\dot{\omega} - T_D$

For Rx Wheel: $T_m = J_w(\dot{\Omega} + \dot{\omega})$

Combining

$$T_D - J_v\dot{\omega} = J_w(\dot{\Omega} + \dot{\omega})$$
$$J_\omega\dot{\Omega} + J_w\dot{\omega} + J_v\dot{\omega} = T_D$$
$$(J_\omega + J_v)\dot{\omega} = T_D - J_w\dot{\Omega}$$

$$\boxed{\dot{\omega} = \frac{T_D - J_w\dot{\Omega}}{J_w + J_v}}$$

Note that for no torque

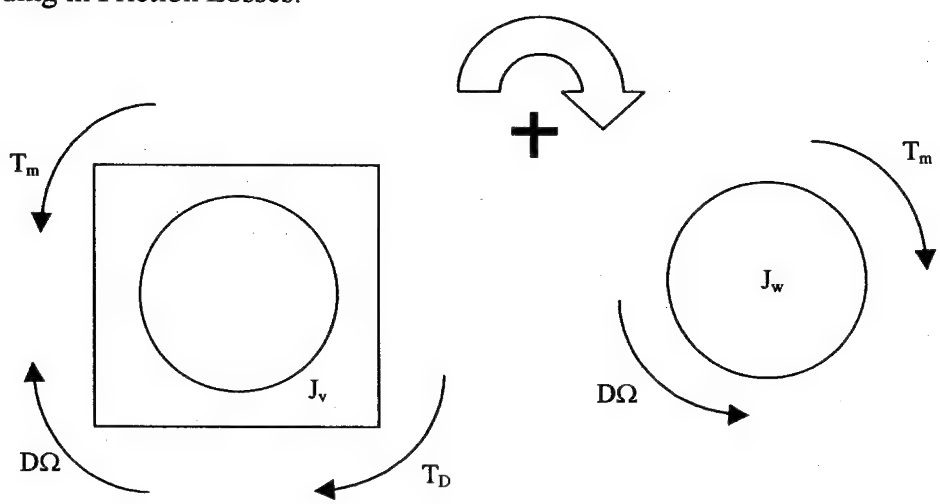
$$\dot{\omega} = \frac{-J_w \dot{\Omega}}{J_w + J_v}$$

$$(J_\omega + J_v)\dot{\omega} = -J_w \dot{\Omega}$$

$$\underbrace{J_w(\dot{\omega} + \dot{\Omega})}_{\text{Wheel Momentum}} + \underbrace{J_v \dot{\omega}}_{\text{Sat Momentum}} = 0$$

Momentum is conserved! (under ideal conditions)

Adding in Friction Losses:



T_m = motor torque
T_D = disturbance torque
$D\Omega$ = drag torque (proportional to motor speed Ω - friction losses)

$$-T_m + D\Omega + T_D = J_v \dot{\omega} \qquad T_m - D\Omega = J_w(\dot{\Omega} + \dot{\omega})$$

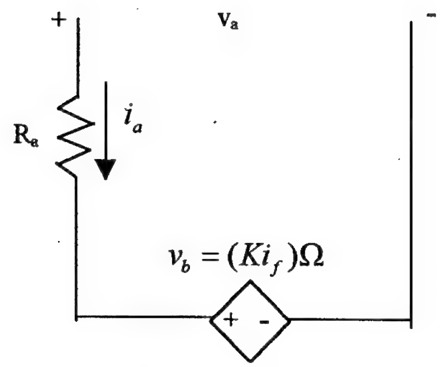
$$T_D = T_m + J_v \dot{\omega} - D\Omega \quad \textbf{\textit{(eqtn 6-1)}} \qquad T_m = J_w(\dot{\Omega} + \dot{\omega}) + D\Omega \quad \textbf{\textit{(eqtn 6-2)}}$$

Motor Dynamics:

DC motor with torque proportional to armature current.

$T_m = (Ki_f)i_a$ $\quad K =$ gain $\quad i_f =$ field current = constant $\quad i_a$ = armature current

$v_b = (Ki_f)\Omega$ = voltage drop of motor $\quad v_a$ = input voltage $\quad R_a$ = resistance in windings



using KVL

$$v_a - i_a R_a - Ki_f\Omega = 0$$

$$i_a R_a = v_a - Ki_f\Omega$$

$$i_a = \frac{v_a}{R_a} - \frac{Ki_f}{R_a}\Omega$$

Substituting for i_a into the motor torque equation $T_m = (Ki_f)i_a$

$$T_m = (Ki_f)\left[\frac{v_a}{R_a} - \frac{Ki_f}{R_a}\Omega\right]$$

$$T_m = \left(\frac{Ki_f}{R_a}\right)v_a - \frac{(Ki_f)^2}{R_a}\Omega \qquad \textit{(eqtn 6-3)}$$

Combining Motor Dynamics with Spacecraft and Rx Wheel Dynamics:

Substitute equation 6-3 into equation 6-1 for T_m.

$$T_D = \left(\frac{Ki_f}{R_a}\right)v_a - \frac{(Ki_f)^2}{R_a}\Omega + J_v\dot{\omega} - D\Omega$$

$$T_D = \left(\frac{Ki_f}{R_a}\right)v_a - \left[\frac{(Ki_f)^2}{R_a} + D\right]\Omega + J_v\dot{\omega}$$

solve for $\dot{\omega}$

$$J_v\dot{\omega} = T_D - \left(\frac{Ki_f}{R_a}\right)v_a + \left[\frac{(Ki_f)^2}{R_a} + D\right]\Omega$$

$$\dot{\omega} = \frac{T_D}{J_v} - \frac{1}{J_v}\left(\frac{Ki_f}{R_a}\right)v_a + \frac{1}{J_v}\left[\frac{(Ki_f)^2}{R_a} + D\right]\Omega \qquad \textbf{\textit{(eqtn 6-4)}}$$

Now substitute equation 6-3 into equation 6-2 for T_m.

$$\left(\frac{Ki_f}{R_a}\right)v_a - \frac{(Ki_f)^2}{R_a}\Omega = J_w(\dot{\Omega} + \dot{\omega}) + D\Omega$$

solve for $\dot{\Omega}$

$$J_w\dot{\Omega} = \left(\frac{Ki_f}{R_a}\right)v_a - \left[\frac{(Ki_f)^2}{R_a} + D\right]\Omega - J_w\dot{\omega}$$

$$\dot{\Omega} = \frac{1}{J_w}\left(\frac{Ki_f}{R_a}\right)v_a - \frac{1}{J_w}\left[\frac{(Ki_f)^2}{R_a} + D\right]\Omega - \dot{\omega} \qquad \textbf{\textit{(eqtn 6-5)}}$$

substitute equation 6-4 for $\dot{\omega}$ in equation 6-5

$$\dot{\Omega} = \frac{1}{J_w}\left(\frac{Ki_f}{R_a}\right)v_a - \frac{1}{J_w}\left[\frac{\left(Ki_f\right)^2}{R_a} + D\right]\Omega - \frac{T_D}{J_v} + \frac{1}{J_v}\left(\frac{Ki_f}{R_a}\right)v_a - \frac{1}{J_v}\left[\frac{\left(Ki_f\right)^2}{R_a} + D\right]\Omega$$

$$\dot{\Omega} = -\frac{T_D}{J_v} + \left(\frac{1}{J_w} + \frac{1}{J_v}\right)\left(\frac{Ki_f}{R_a}\right)v_a - \left(\frac{1}{J_w} + \frac{1}{J_v}\right)\left[\frac{\left(Ki_f\right)^2}{R_a} + D\right]\Omega \qquad \textit{(eqtn 6-6)}$$

Let $A = \dfrac{Ki_f}{R_a}$ $\qquad B = \dfrac{\left(Ki_f\right)^2}{R_a} + D$

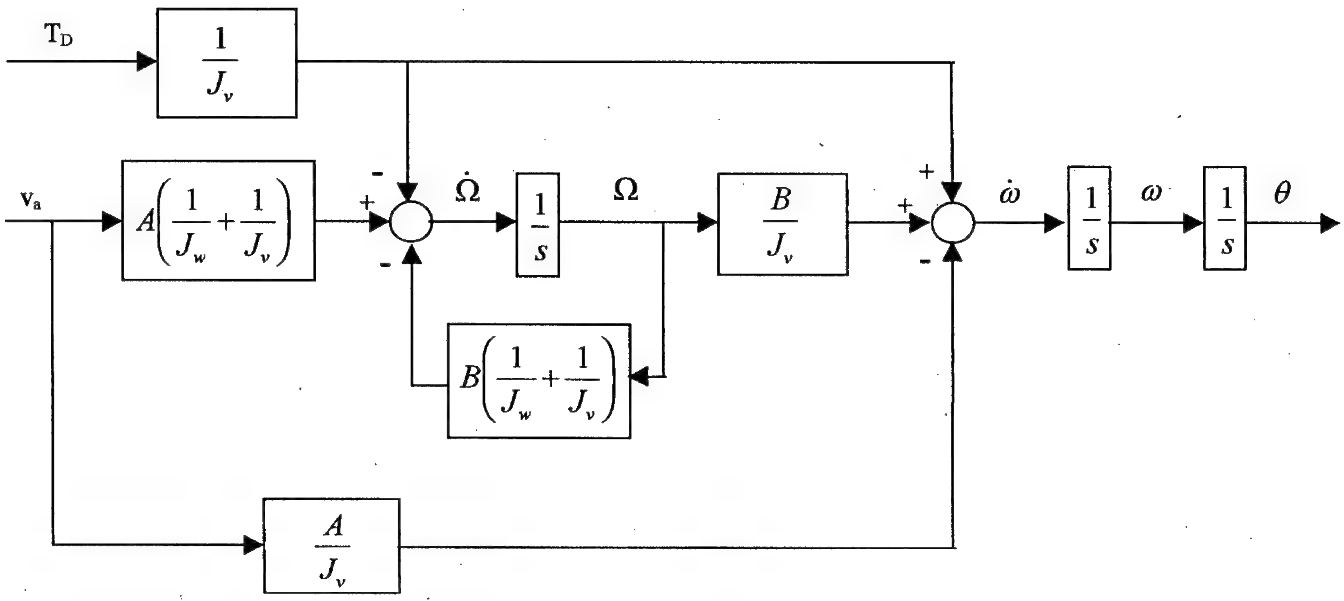
Substitute A and B above into equations 6-4 and 6-6.

$$\dot{\omega} = \frac{T_D}{J_v} - \frac{1}{J_v}Av_a + \frac{1}{J_v}B\Omega \qquad \textit{(eqtn 6-7)}$$

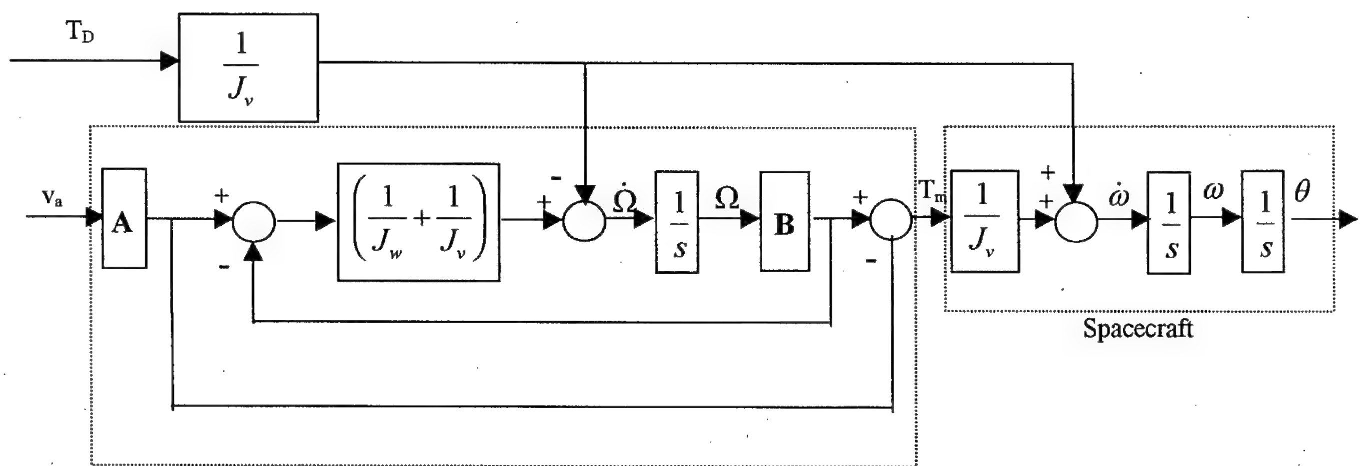
$$\dot{\Omega} = -\frac{T_D}{J_v} + \left(\frac{1}{J_w} + \frac{1}{J_v}\right)Av_a - \left(\frac{1}{J_w} + \frac{1}{J_v}\right)B\Omega \qquad \textit{(eqtn 6-8)}$$

6.2.2 Reaction Wheel System Block Diagram

Use equations 6-7 and 6-8

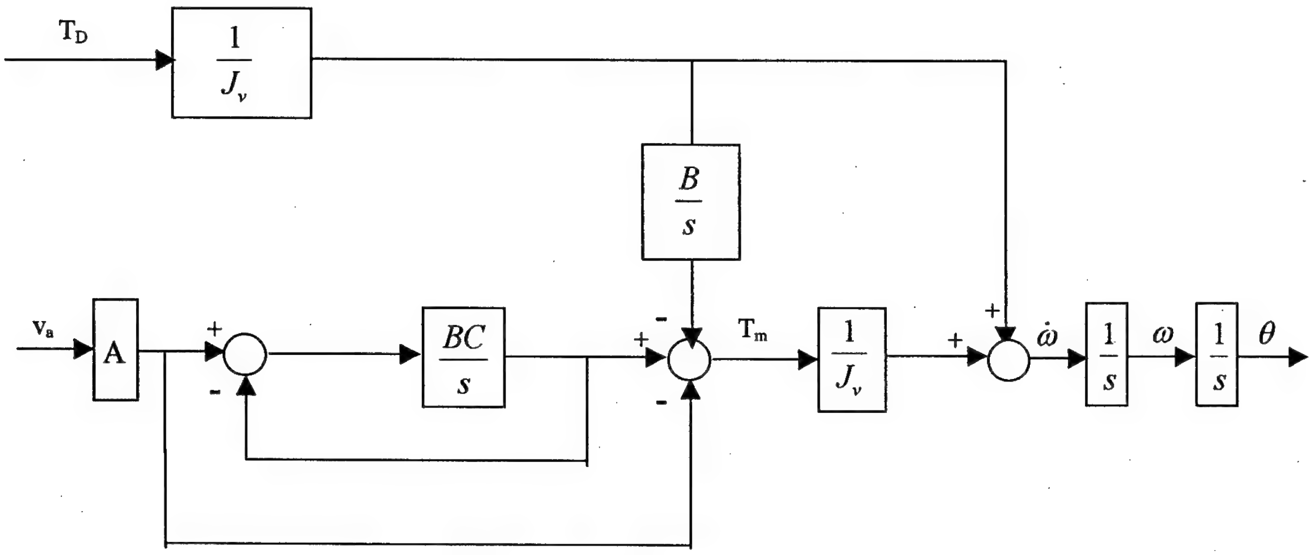


Simplifying:

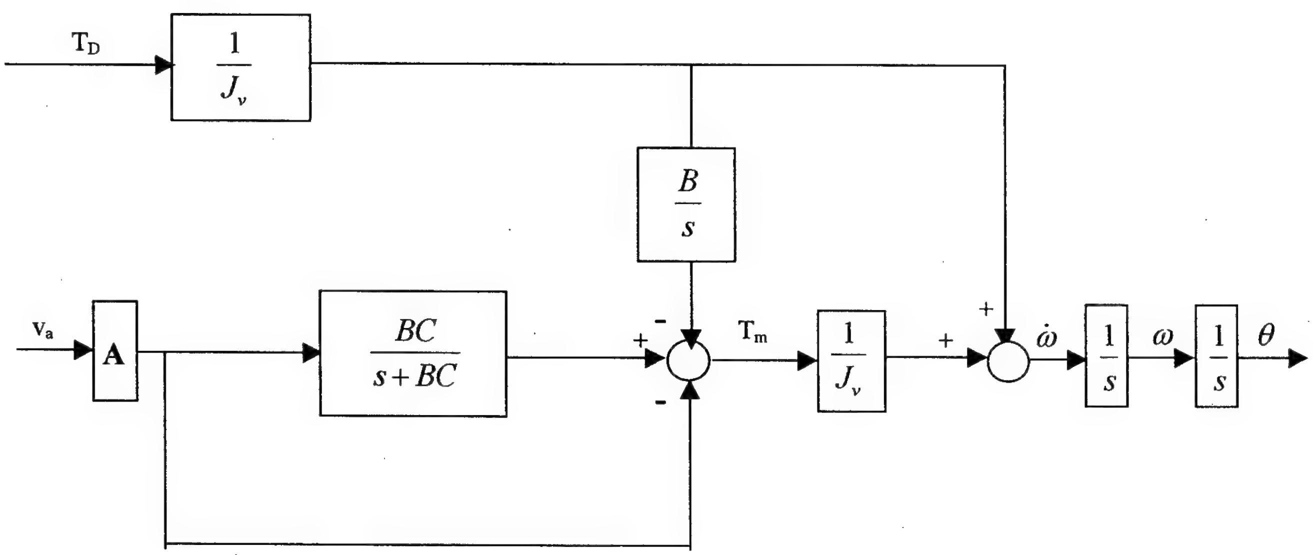


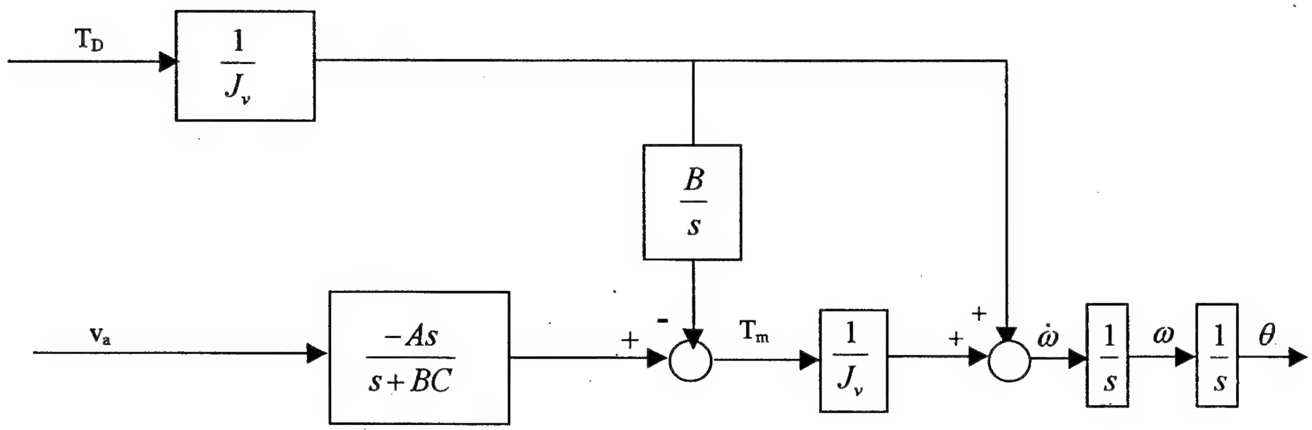
Rx Wheel & Motor

Let $C = \frac{1}{J_w} + \frac{1}{J_v}$ and further simplify

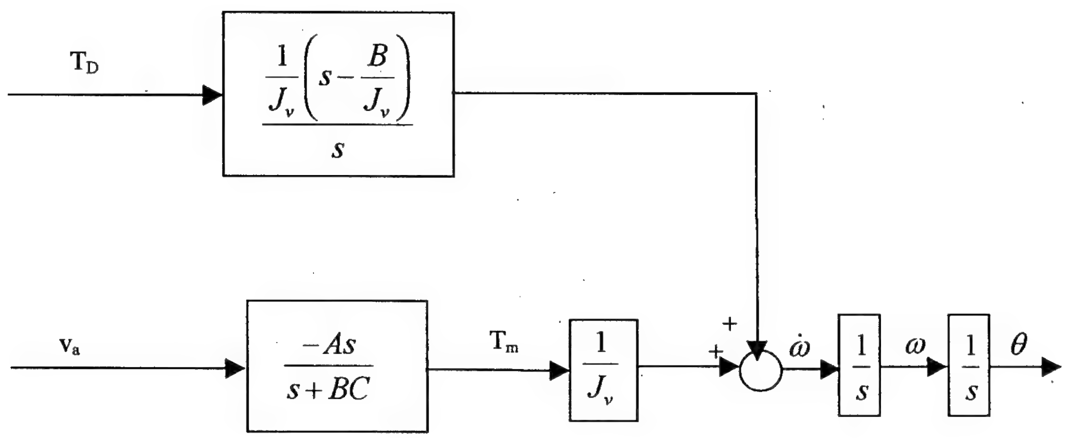


Further simplifying:



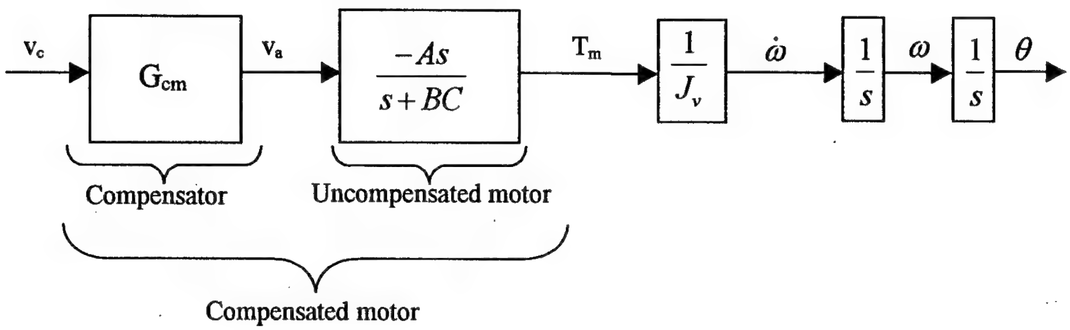


Further combining blocks:



Note that the Rx wheel motor is uncompensated. We can add a compensator (G_{cm}) to allow us to treat the Rx wheel and compensated motor as just a constant! Then we will have a simple 2nd order system to contend with.

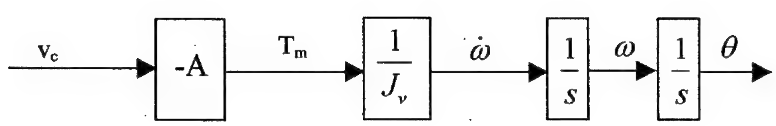
Let's ignore disturbance torque for now. We now have the following:



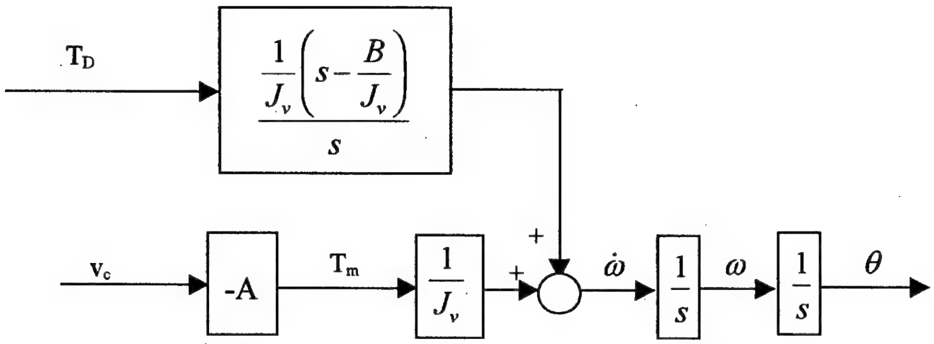
V_c is now the command voltage

Let $G_{cm} = \dfrac{s+BC}{s}$ (which is just a *proportional* + *integral* controller)

Therefore, the resulting compensated motor can be represented as just a gain (-A) and we greatly simplify the mathematical representation of the system making it second order. Then, we have the following simplified system when we compensate the Rx wheel motor.



Adding back in the disturbance torque we get:



When we determine the actual motor parameters, the value $\dfrac{B}{J_v}$ will be small and we will be able to ignore it. This will greatly simplify our analysis of disturbance torques.

6.2.2 Motor Parameter Dynamics

From equation 1-2, if we hold the spacecraft still ($\omega = 0$), we get the following relationship for T_m:

$$T_m = J_w\dot{\Omega} + D\Omega$$

and from equation 1-3 we know $T_m = \left(\dfrac{Ki_f}{R_a}\right)v_a - \dfrac{(Ki_f)^2}{R_a}\Omega$

Equating the two we get:

$$J_w\dot{\Omega}+D\Omega=\left(\frac{Ki_f}{R_a}\right)v_a-\frac{\left(Ki_f\right)^2}{R_a}\Omega$$

Assume $\Omega(0)=0$ (i.e. start the wheel from a dead stop)

$$\mathrm{J}_w s\Omega(s)+D\Omega(s)+\frac{(Ki_f)^2}{R_a}\Omega(s)=\frac{Ki_f}{R_a}v_a$$

And simplifying

$$\mathrm{J}_w s\Omega(s)+\left(D+\frac{(Ki_f)^2}{R_a}\right)\Omega(s)$$

Recall $A=\dfrac{Ki_f}{R_a}$ $\qquad B=\dfrac{\left(Ki_f\right)^2}{R_a}+D$

Therefore

$$\mathrm{J}_w s\Omega(s)+B\Omega(s)=Av_a$$
$$\Omega(s)[\mathrm{J}_w s+B]=Av_a$$

$$\boxed{\frac{\Omega(s)}{v_a}=\frac{A}{\mathrm{J}_w s+B}=\frac{0.0624}{(0.1816)s+0.0096}}$$

Test using a step response to determine A and B.

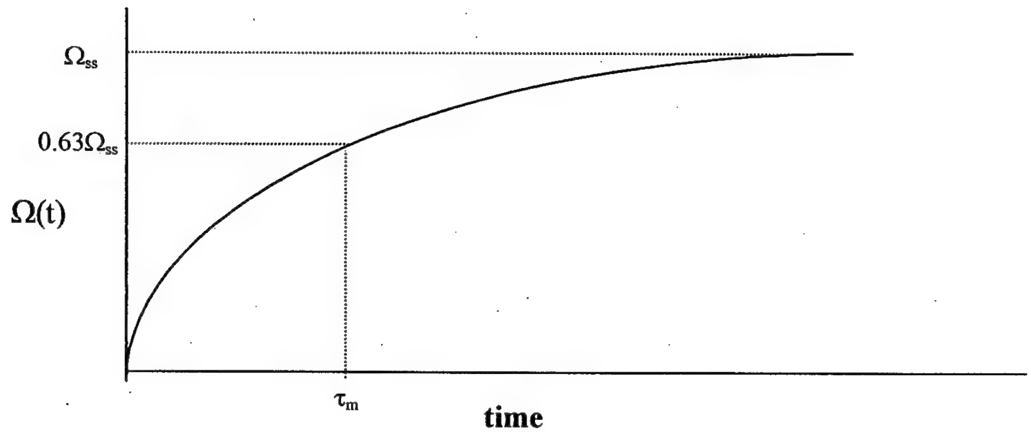
$$\frac{A/J_w}{s+B/J_w}=\frac{0.344(0.35)}{s+0.053}=\frac{\Omega}{v_a}\cdot\frac{V_\Omega}{\Omega}=\frac{V_\Omega}{v_a}$$

$$\Omega_{ss}=\frac{v_a A}{B}\quad\Rightarrow\quad\frac{\Omega_{ss}}{v_a}=\frac{A}{B}$$

and

$$\frac{\frac{A}{B}}{\frac{J_w}{B}s+1}=\frac{\Omega(s)}{v_a(s)}\quad\Rightarrow\quad\tau_{\mathrm{m}}=\frac{J_w}{B}=\text{ time constant}$$

and the time response for a step voltage input (v_a) should look as follows:



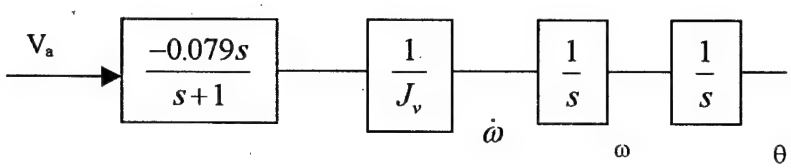
Therefore, we can determine A and B from this plot. See Section 5.3 for testing procedure and results.

7.0 Controller Design

7.1 Specific Reaction Wheel Controller Design

7.1.1 PI Controller

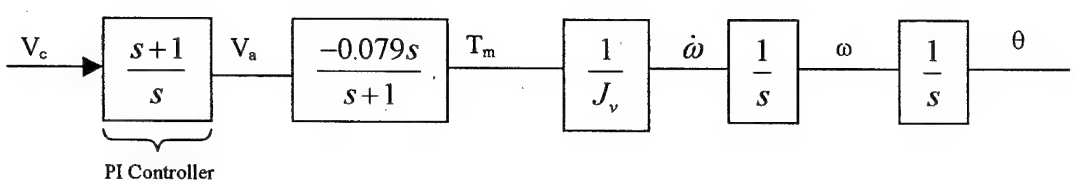
From the following block diagram, it is evident that a PI controller would be useful in eliminating the first block.



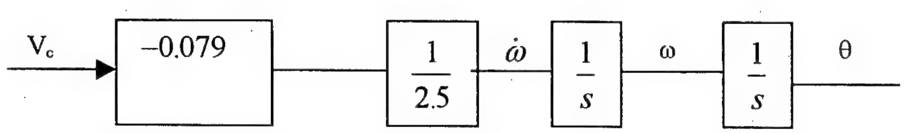
=> PI controller

$$G_{cm} = \frac{s+1}{s}$$

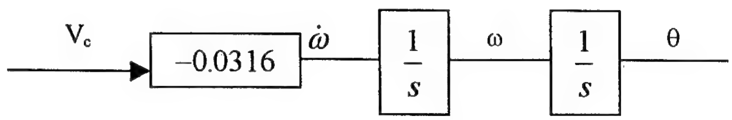
Add P+I controller to the above block diagram.



The PI controller eliminates the zero and pole simplifying to,



Further simplifying,



From this block diagram, it is known that

$$\dot{\omega} = -0.0316 V_c$$

7.1.2 Lead Compensator

In using lead compensation, the intent is to change the phase plot of a Bode phase response to reduce the percent overshoot while increasing the response time.

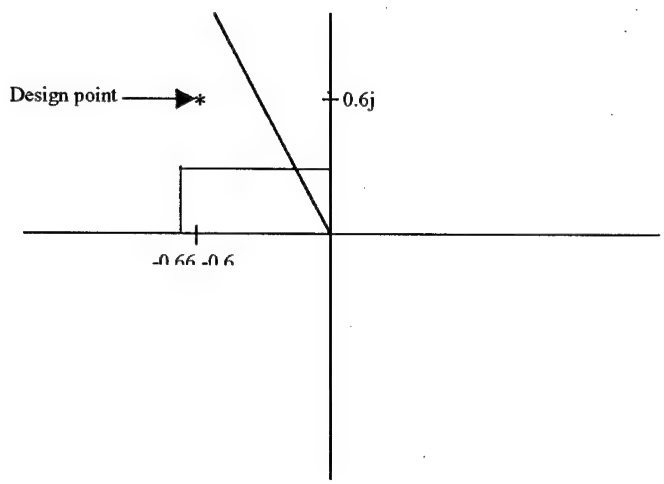
<u>Specifications</u>

$$T_R < 5\,\text{sec}$$
$$PO < 20\%$$

From the definition of σ and $\omega_{d,}$

$$\sigma = \frac{3.3}{T_R} = 0.66$$

$$\omega_d = \frac{\pi}{2 \cdot T_R} = .031$$



$$s = -0.6 \pm 0.6j$$
$$G = \frac{-0.0316}{s^2}$$

This yields a phase change of -270°. We want an angle of 0°, since this system uses positive feedback and there is a negative forward path.

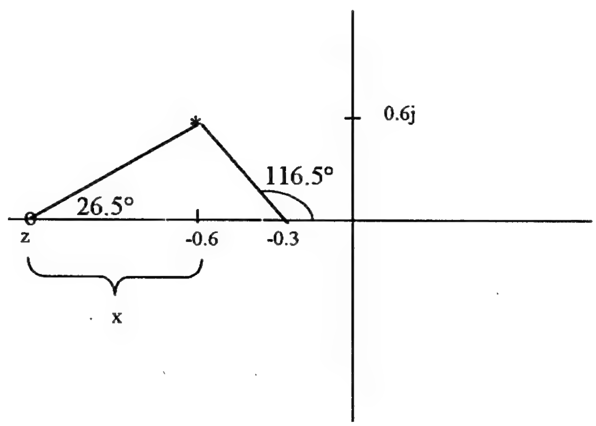
G_c = transfer function of compensator

G = transfer function of system

H = feedback gain

$$|G_c GH| = 1$$
$$\angle G_c G = 0$$
$$\angle = -270 + (-180) = -450 = -90$$

Need to add +90°. Lead compensation.

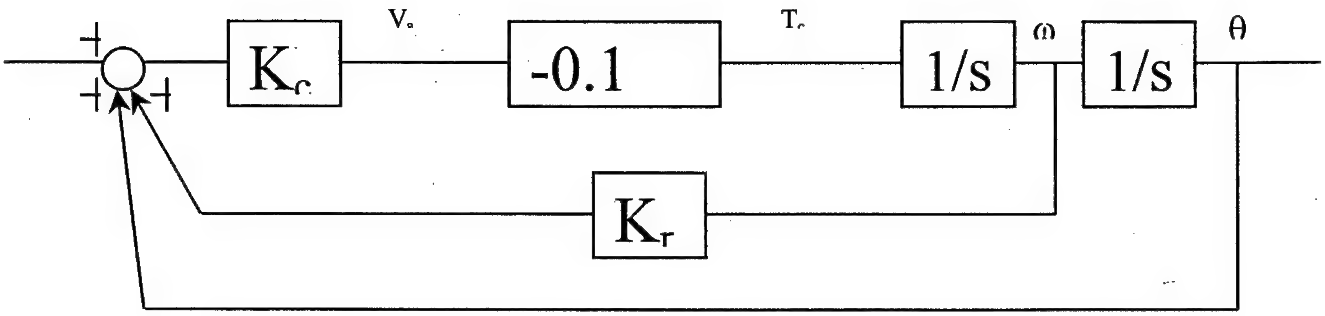


Using the above design point, s=-0.6+0.6j, and choosing a pole at –0.3, the zero must be at –1.8 with a resulting gain of 11.2 as follows.

Root Locus plots demonstrate the movement of the poles as the gain is increased. Since there is a negative forward path and positive feedback, the 'rlocus' command on MATLAB must contain the negative value for the open loop transfer function.

7.2 Reaction Wheel Control

Block Diagram



$$V_a = K_r \omega K_c + K_c \theta$$

$$\theta = x_1$$
$$\dot{\theta} = \omega = x_2$$

$$T_c = -0.1 V_a \qquad \& \qquad T_c = \ddot{\theta}$$

$$T_c = -0.1\left[K_r \omega K_c + K_c \theta\right]$$
$$T_c = -0.1 K_r K_c \omega - 0.1 K_c \theta$$
$$T_c = -0.1 K_r K_c x_2 - 0.1 K_c x_1$$

$$\ddot{\theta} = \dot{x}_2 = -0.1 K_r K_c x_2 - 0.1 K_c x_1$$

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -0.1 K_c & -0.1 K_r K_c \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}$$

$$[sI - A] = \begin{bmatrix} s & -1 \\ 0.1K_c & s + 0.1K_c K_r \end{bmatrix}$$

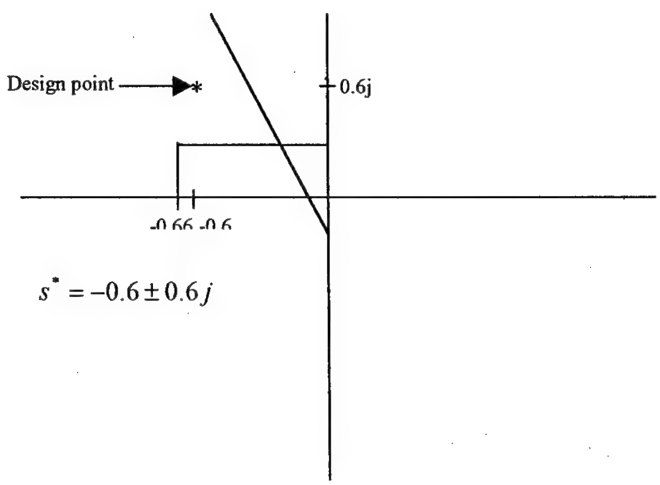
$$|sI - A| = s(s + 0.1K_c K_r) + 0.1K_c$$

$$s^2 + 0.1K_c K_r s + 0.1K_c$$

Specs

$$T_r < 5\sec \qquad \sigma \geq \frac{3.3}{T_r} = .66$$

$$PO < 20\% \qquad \omega_d = \frac{\pi}{2T_r} = 0.31$$



$$s^* = -0.6 \pm 0.6j$$

$s^* = -0.6 \pm 0.6j$

$s^2 + 1.2s + 0.72 = s^2 + 0.1K_cK_rs + 0.1K_c$

$0.1K_c = .072$

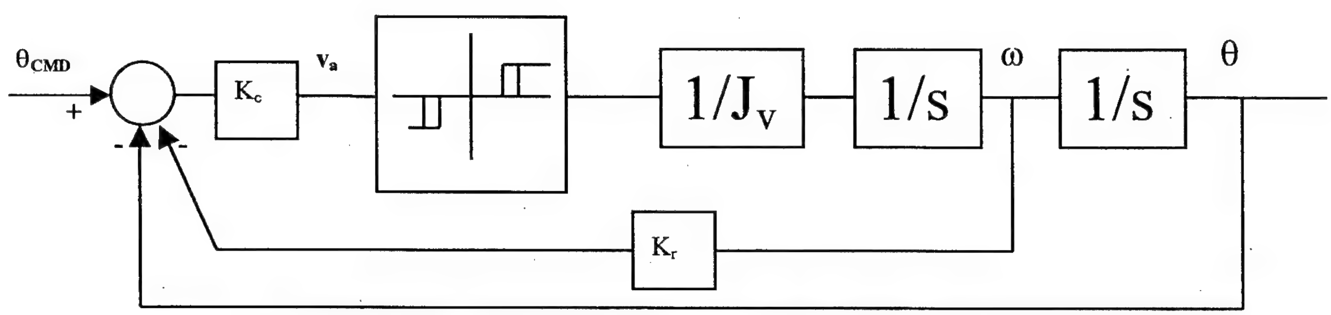
$$\boxed{K_c = 7.2}$$

$1.2 = 0.1K_cK_r = 0.1(7.2)K_r$

$$\boxed{K_r = 1.67}$$

7.3 Gas Jets Control

Block Diagram with Gas Jets



And the control law (for zero input)

$$V_a = -K_c(\theta + K_r\dot{\theta})$$
$$= -K_c\theta - K_cK_r\dot{\theta}$$

Using equation of motion for torque and inertia yields the following relationship;

$$J_v \ddot{\theta} = T_c$$

Converting to state variables, let

$$\theta = x_1$$
$$\dot{\theta} = x_2 = \omega$$

then

$$\dot{x}_1 = x_2$$
$$x_2 = \frac{1}{J_v} T_c$$

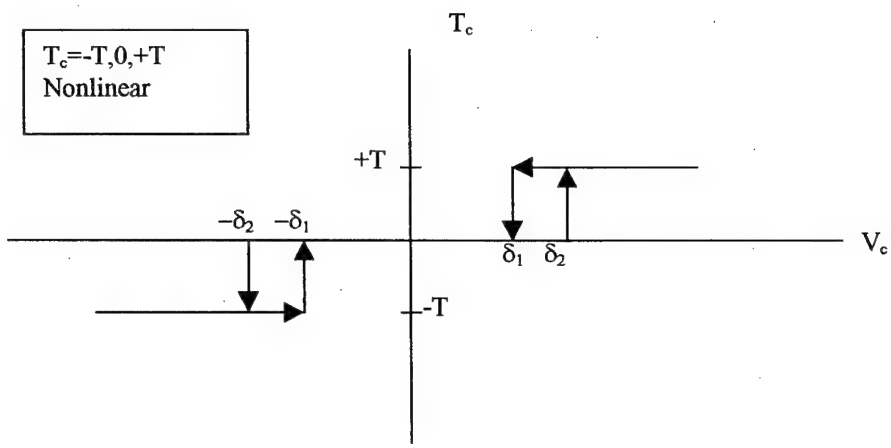
Substituting into V_a gives,

$$\boxed{V_a = -K_c x_1 - K_c K_r x_2}$$

In matrix form

$$V_a = \begin{bmatrix} -K_c & -K_c K_r \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}$$

T_c is nonlinear and has the following model with hysteresis;



Lets look at all three possibilities for T_c.

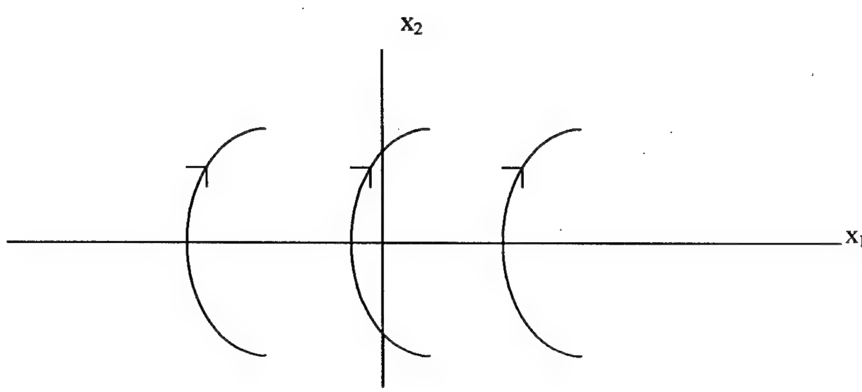
For $T_c = +T$

$$\dot{x}_1 = x_2 \qquad \dot{x}_2 = \frac{T}{J_v} \quad => \quad \frac{dx_1}{dt} = x_2 \Rightarrow dt = \frac{dx_1}{x_2} \qquad \frac{dx_2}{dt} = \frac{T}{J_v} \Rightarrow dt = \frac{dx_2}{T} J_v$$

Using algebra, this simplifies to:

$$x_2^2 = \frac{2T}{J_v} x_1 - \frac{2T}{J} x_1(0) + x_2^2(0)$$

which is a family of parabolas in the form $y^2 = kx + c$.



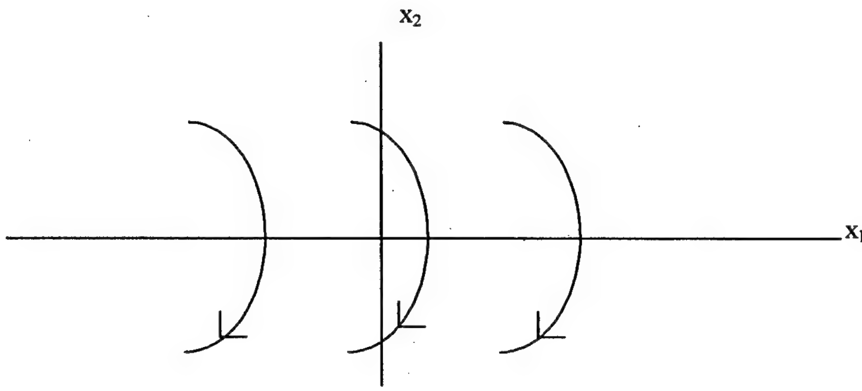
For $T_c = -T$

$$\dot{x}_1 = x_2 \qquad \dot{x}_2 = \frac{-T}{J_v} \quad => \quad \frac{dx_1}{dt} = x_2 \Rightarrow dt = \frac{dx_1}{x_2} \qquad \frac{dx_2}{dt} = \frac{-T}{J_v} \Rightarrow dt = -\frac{dx_2}{T} J_v$$

And this simplifies to:

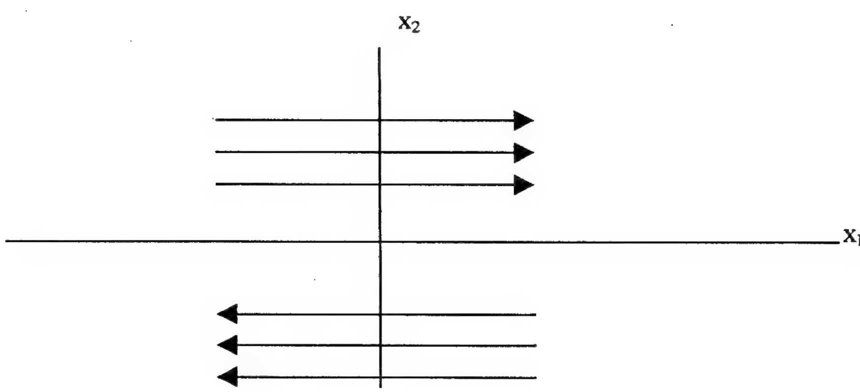
$$x_2^2 = -\frac{2T}{J_v} x_1 + \frac{2T}{J} x_1(0) + x_2^2(0),$$

This is another family of parabolas



<u>Finally for $T_c = 0$</u>

$$\begin{aligned}\dot{x}_1 &= x_2 \\ \dot{x}_2 &= 0\end{aligned} \quad \Rightarrow \quad \frac{dx_2}{dx_1} = 0$$



Now analyze control in the phase plane.

For $V_a = +\delta_2$

From control law;

$$+\delta_2 = K_c x_1 - K_c K_r x_2$$

$$x_1 = \frac{-\delta_2}{K_c} - K_r x_2$$

This is the equation for a switching line. Since $V_a = +\delta_2$, this represents the line where the control torque (T_c) goes from OFF to ON in the "+" direction.

Applying the same approach, we come up with switching lines for the other δ's.

For $V_a = +\delta_1$

$$x_1 = \frac{-\delta_1}{K_c} - K_r x_2$$

For $V_a = -\delta_2$

$$x_1 = \frac{\delta_2}{K_c} - K_r x_2$$

For $V_a = -\delta_1$

$$x_1 = \frac{\delta_1}{K_c} - K_r x_2$$

To summarize:

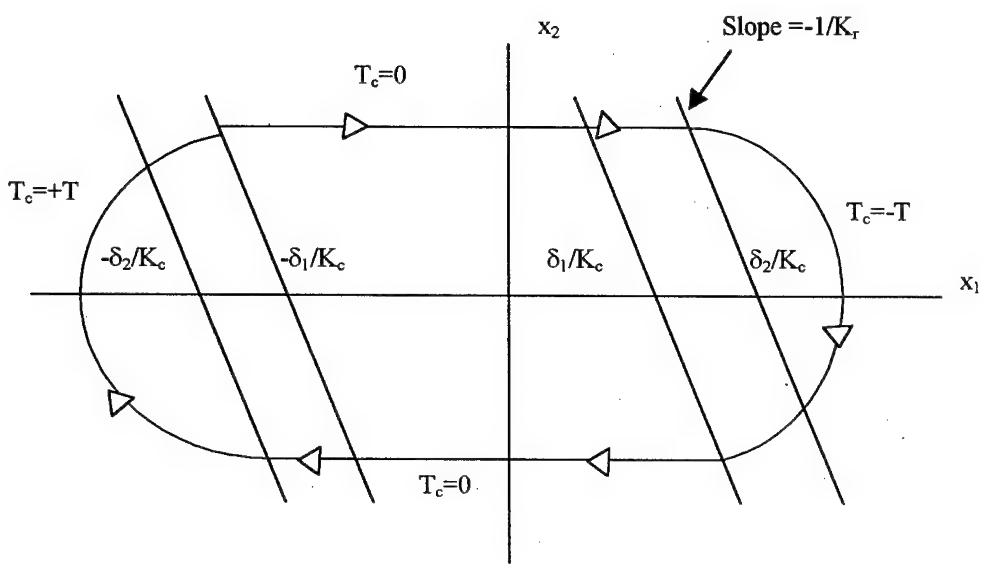
$$V_a = +\delta_2 \Rightarrow x_1 = \frac{-\delta_2}{K_c} - K_r x_2$$

$$V_a = +\delta_1 \Rightarrow x_1 = \frac{-\delta_1}{K_c} - K_r x_2$$

$$V_a = -\delta_2 \Rightarrow x_1 = \frac{\delta_2}{K_c} - K_r x_2$$

$$V_a = -\delta_1 \Rightarrow x_1 = \frac{\delta_1}{K_c} - K_r x_2$$

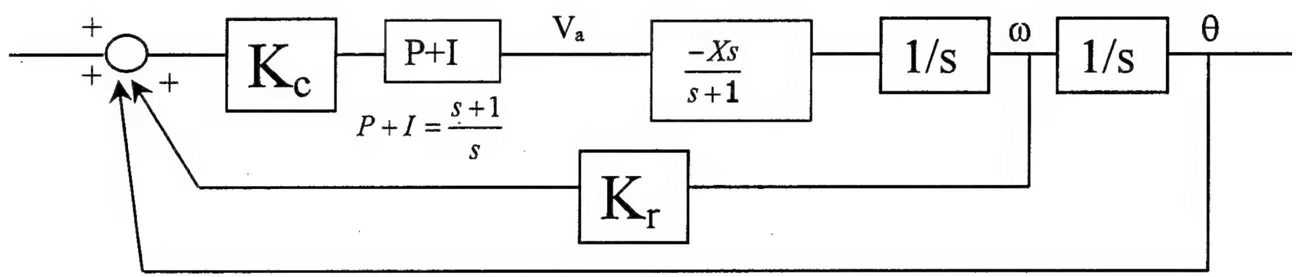
Plotting these switching lines in the phase plane:

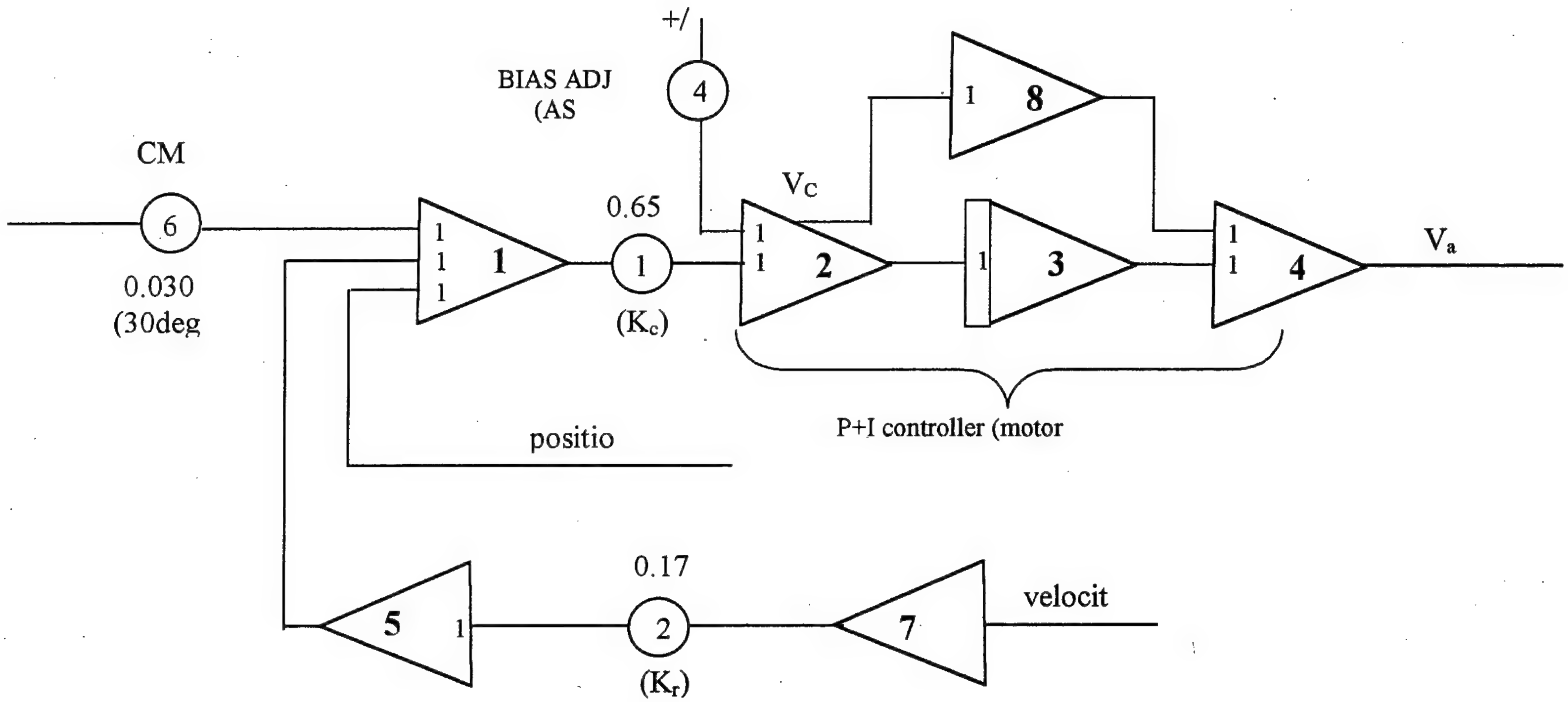


This spiraling continues until you reach a limit cycle in which case the satellite oscillates back and forth between $\pm\theta_{max}$.

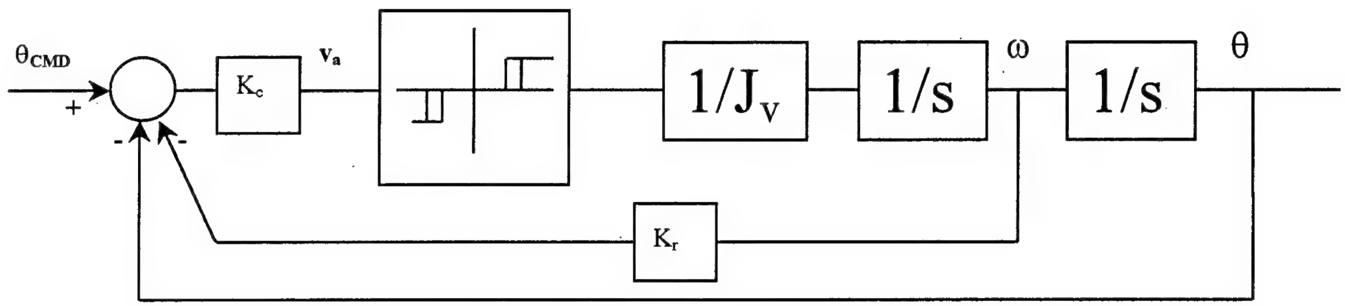
$$\theta_{max} = \frac{J_v}{8TK_r^2}\left(\frac{\delta_2 - \delta_1}{K_c}\right)^2 + \frac{\delta_2 + \delta_1}{2K_c}$$

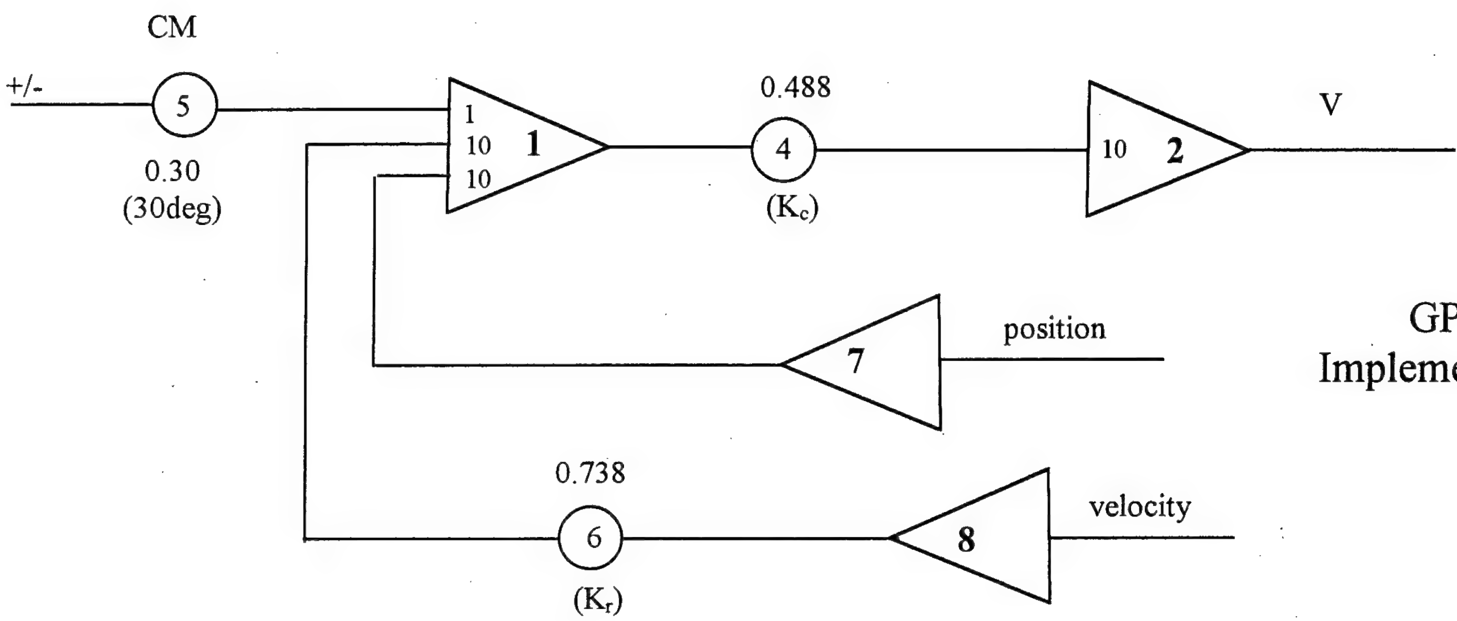
7.4 Reaction Wheel Controller & Implementation





7.4 Gas Jet Controller & Implementation





GP-6
Implementation

8.0 Evaluation Plan

The Evaluation Plan is the method by which the system is tested to ensure that it performs the desired functions according to specifications. Any deviations from the specifications are noted here along with the tests performed to meet the specs.

8.1 Manual Controller

The manual controller was designed to allow the user to control SADSaC with his/her fingertips. This also lent for the opportunity to make sure the entire system was wired properly. Using the manual controller, the gas jet system and the reaction wheel system were tested immediately after assembly was completed. Initial tests revealed that the gain on the servo amplifier was not properly adjusted so the reaction wheel would not move and two of the gas jets did not fire. This was resolved by cranking up the gain on the servo amp, thus pumping more current to the motor and a bad solder was fixed on the Gas Jet Thruster circuit. With these corrections, SADSaC functioned as it should have at that time.

8.2 Reaction Wheel Controller

With the goal being ±0.5° accuracy for this controller, it is a relatively difficult task with all of the uncertainties. A few things that affect this control problem are the physical imbalance in the satellite causing it to drift one direction and a bias in the GP-6. This bias causes the controller to think it is working when is actually is not.

These problems were all corrected. The bias was eliminated by adding a signal equal in magnitude, but opposite in sign to drive the bias to zero. The imbalance was

reduced by cranking up the gain on the servomotor giving more wheel speed for a given error signal. In the end a ±0.4° accuracy was achieved meeting the system requirement.

8.3 Gas Jet Controller

The gas jet controller had the same requirements and the same problems to overcome as the reaction wheel controller, as well as a few of its own. The clockwise gas jets would chatter when the command signal was between $+\delta_2$ and $+\delta_1$. This problem didn't affect the control too much, it was just uncomfortably noisy. This problem is still being worked out.

In any case, with the deadband on the controller circuit set at ±1.V, the best accuracy achievable was nearly ±0.9°. This didn't meet the requirement, but was close enough do to the problem with the chattering.

9.0 Conclusion

9.1 Opportunities for Further Investigation - Recommended Improvements

9.1.1 Optical Sensor

The addition of an optical sensor would be and interesting addition to SADSaC. Designing a control scheme to have SADSaC turn to follow a person with a flashlight could simulate tracking a fixed point on the Earth, or sun-sensing during the initial attitude determination of a spacecraft. SADSaC was built to allow for this type of expansion.

9.1.2 Fix Chatter of Gas Jets

One of the most difficult problems in the design is overcoming the chatter caused in the hysteresis band of the gas jet controller circuit. Although not causing too many problems in the control portion of the project, there is some concern that this switching action may damage some of the circuitry or the solenoids, not to mention the fact that it is noisy. A solution to this problem would improve SADSaC's overall performance as an educational tool.

9.1.3 Replace Reaction Wheel Tachometer

The current tachometer for reaction wheel velocity feedback was left over from a previous project and is extremely noisy electronically. So noisy in fact, that at high velocities it generates enough AC to induce spikes in the other signal lines running down the pipe. One of those lines being the gas jet command and this also causes the gas jets to chatter. The noise also makes it impossible to get a clean signal for

reaction wheel velocity feedback needed for momentum dumping. It is suggested that a new tach, similar the one used for the satellite velocity, be purchased to replace it.

9.2 Commentary

This project, from the perspective of a relatively inexperienced engineer, was an extremely worthwhile undertaking. First it encompasses the entire spectrum of the engineering process, starting from the requirements and ending with operation. The experience gained in working with the people building the skeletal structure; having to compromise on certain design features as to make their job as easy as possible while still meeting the requirements, was putting to practice the idea of making sure the machinist could build what was designed. Seeking out help from the "experts" when forward progress halted in a circuit design and working until it worked, not the end of the class period as before, all helped to make this a tremendous engineering experience.

As the author of this paper, I can say with certainty that working on this project gave me extensive insight in to the work of an engineer.

10.0 Acknowledgments

The following people played an important role in this project. A Thanks goes out to each of them. The names are listed in alphabetical order.

Becker, Steve; SSgt, USAF: NCOIC Research, USAFA - Created printed circuit boards from schematics.

Bloom, Jim; Major, USAF – Project supervisor.

Hemlock, Dave; MSgt, USAF: Supt. of Labs, USAFA.

Trudeau, Jon; Dept. of Electrical Engineering, USAFA - Electrical Engineering support and reference.

Webb, Homer; Training Devices, USAFA - Engineering machine shop work, constructed SADSaC skeleton.